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STUDY AND DEVELOPMENT OF TURBOFAN NACELLE MODIFICATIONS TO MINIMIZE FAN-COMPRESSOR NOISE RADIATION

Volume VI – Economic Studies

Prepared by
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16. Abstract The economic implications of installing treated nacelles, as developed under Contract NAS 1-7129, on Boeing 707-320B airplanes powered by P & WA JT3D-3B engines are studied. Operating costs are estimated for the year 1972. It was found that international direct operating costs (DOC) increase by 9.2 percent and domestic DOC increase by 9.6 percent. The major factor in these increases is the increase of depreciation cost. The additional depreciation cost is based on a predicted total installed retrofit price for 1972 of $1 million per airplane. The increase of indirect operating costs due to the retrofit is considered to be negligible. A hypothetical fleet study shows that a small loss of revenue earning capacity is involved, particularly over long range stages. For the route network considered in the study, a 0.1 percent loss of passenger revenue, a 4.3 percent increase of total operating costs and a 4.3 percent reduction in return based on passenger revenue is estimated.

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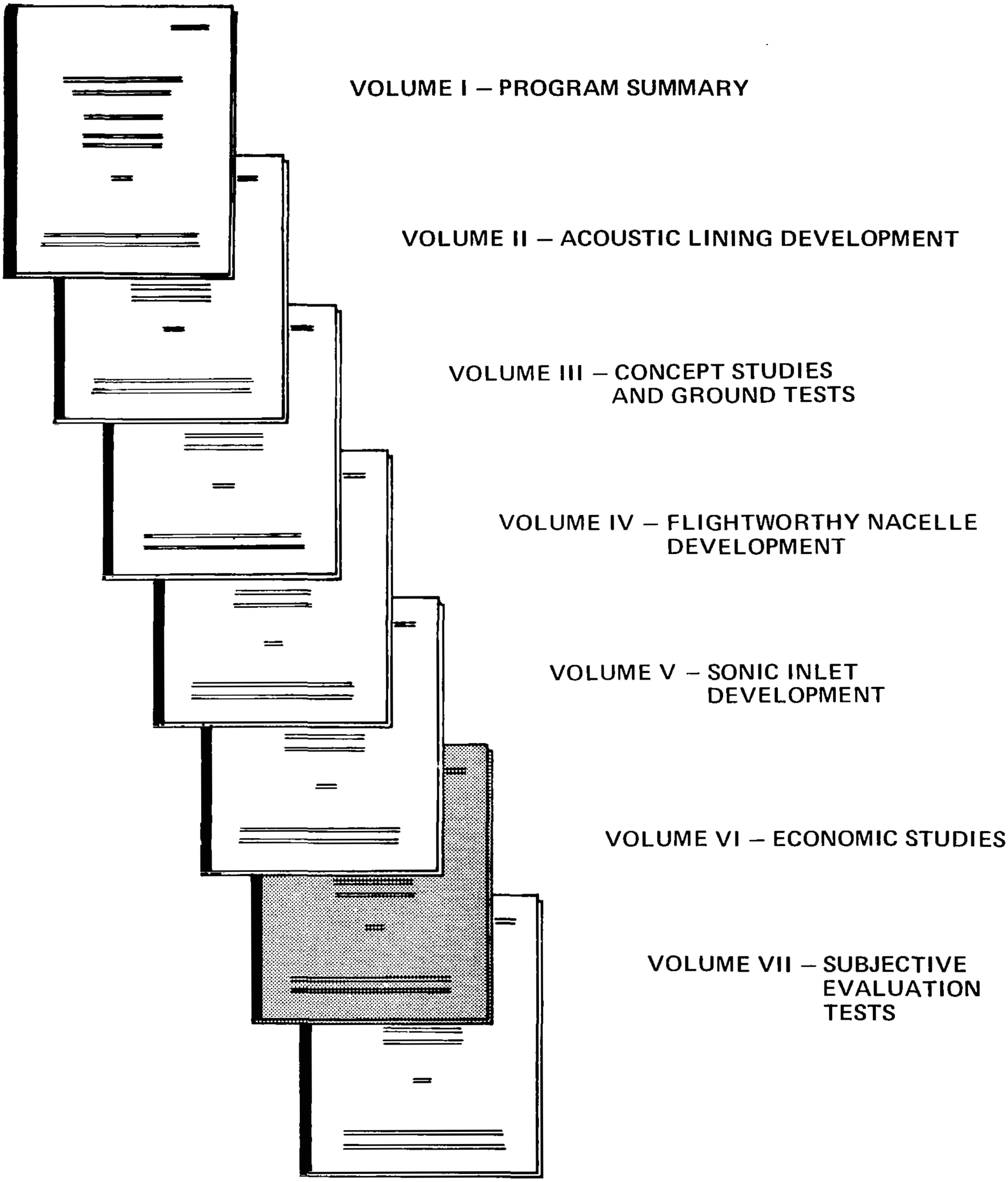

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STUDY AND DEVELOPMENT OF TURBOFAN NACELLE MODIFICATIONS TO MINIMIZE FAN-COMPRESSOR NOISE RADIATION

VOLUME VI

ECONOMIC STUDIES

The Boeing Company
Seattle, Washington

SUMMARY

National Aeronautics and Space Administration Contract NAS 1-7129 specified that the operational and economic effects on airline operations of nacelle modifications, whose development and performance are discussed in volume IV, be investigated. The airplane chosen for the study was the 707-320B powered by Pratt & Whitney JT3D-3B engines.

This volume presents the results of a theoretical study that compared two fleets of Boeing 707-320B airplanes, one with and one without the acoustically treated nacelles. The treated nacelle includes a two-ring treated inlet and a full-length treated fan duct. The study evaluated a hypothetical airline 707-320B route network operating with a representative passenger yield structure. The results of this study are applicable only to the route structure assumed. Any specific airline having a significantly larger proportion of long-range routes or higher overall load factors would be more severely affected by the incorporation of the treated nacelle. The results of this study show that the 1972 international direct operating cost (DOC) will increase by about 9.2 percent and that this increase is almost entirely due to the depreciation of the retrofit.

It was found that when operating both airplane fleets at the current maximum gross takeoff weight of 327 000 lb, the airplane with the treated nacelle presented some operational restrictions that produced a reduction of revenue-earning capacity. The major factor in economic return was the increase in DOC, which reduced return on revenue by 4.3 percent. This 4.3-percent reduction for the hypothetical carrier may appear small. However, in a narrow-margin industry, a nominal cost increase can produce a drastic impact on return on investment. In the final analysis, a detailed assessment of the economic effect of a treated-nacelle retrofit must be made by each of the affected airlines.

INTRODUCTION

NASA Contract NAS 1-7129 specifies that the nacelle modifications, whose development is discussed in volume IV, be studied to determine their effect on both the direct operating costs of the airplane and the overall operational and economic implications of their use in airline operations. Although the test airplane was equipped with P&WA JT3D-7 engines, it was agreed that the cost and economic studies should be rendered on the JT3D-3B powered airplane, which is much more commonly found in airline service. The studies were done for the Boeing 707-320B model, which is identical in configuration to the test airplane. Figure 1 shows a three-view and general arrangement drawing of the airplane. Figures 2 and 3 show the treated nacelles fitted to the test airplane.

The study considers the effect of nacelle modifications on direct operating costs of the airplane. The study also considers a simulated fleet operation, examining the effect of a retrofit program on both the operational and economic factors of a total airline operation.

The study is necessarily largely theoretical at this stage of treated-nacelle development. Some aspects of the study, particularly those pertaining to airline operation, may be sensitive to some of the many assumptions that had to be made. For this reason, such study needs to be repeated as the technology of treated-nacelle design and development advances and, in the final analysis, a detailed assessment must be made by each of the affected airlines.

SYMBOLS

B	total fleet block hours per day
C	empirical constant defining elements of indirect operating costs
E_W	operating empty weight of the airplane, pounds
EPNdB	unit of effective perceived noise level
EPNL	effective perceived noise level, EPNdB
F	empirical constant defining passenger yield
F(H)	fuel burned in flight + air maneuver, pounds
$F_H(h)$	distribution function of H
FC	first class

G	empirical constant defining passenger yield
H	passenger payload weight demand, pounds
H_P	weight of a full passenger payload, pounds
$H^*(T)$	maximum payload capacity at runway temperature, pounds
J	total passenger denials
J_C	passenger denials due to capacity limits
LF	load factor
M	Mach number
N	number of airplanes
n. mi.	nautical mile
P_i	associated probabilities
Q	passenger demand per trip constant
$S(H)$	reserve fuel required on board, pounds
st. mi.	statute mile
T	temperature, °F
U_A	block hours per day per airplane
W	gross weight of airplane, pounds
W_P	required gross takeoff weight of airplane, pounds
$W^*(T)$	maximum gross takeoff weight, a function of T and the takeoff runway length and altitude, pounds

X_f fuel allowance for taxi-in after touchdown, pounds

μ average passenger demand per trip

σ standard deviation

Subscript

i integer

AIRPLANE OPERATING COSTS

Basic Data Assumptions

General.—Except where specifically noted, all direct operating costs were calculated according to the method of reference 1. The method had to be modified in certain respects to cover the particular case of a treated-nacelle retrofit. Supplemental estimates were made for this purpose. Indirect operating costs were calculated according to recent modifications made to a method developed by Boeing and Lockheed in 1963. The costs were calculated for the current maximum permissible gross weights, that is, for existing- and treated-nacelle airplanes unrestricted by any noise rule assumptions.

All data were adjusted, where possible and as noted, to reflect 1972 costs as being more representative of a probable fleet retrofit program. A 4-percent-per-annum escalation rate for material costs and 5-percent rate for labor costs were assumed.

The airplane studied was a Boeing 707-320B powered with JT3D-3B engines. This airframe/engine combination is very commonly found in airline service, and the effect of a possible retrofit program to this model is obviously important to the airline industry. Inspection of the results shows that the conclusions would not have been materially affected had the JT3D-7 engines of the test airplane been assumed.

Direct operating costs.—The conditions assumed for the DOC studies are listed below. All data assumptions for DOC estimation have been discussed with and agreed upon by NASA and the Douglas Aircraft Division of McDonnell Douglas Corporation to ensure compatibility with the results of NASA Contract NAS 1-7130.

Flight operations:

Wind	Zero
Ambient temperature	Climb, descent, cruise: standard atmosphere Takeoff, missed approach: 84°F
Ambient pressure	Standard atmosphere
Airfield altitude	Sea level
Cruise procedure	Step climb, where applicable, at 31 000, 35 000, and 39 000 ft
Cruise Mach number	0.80 to 0.83
Flight crew cost	As reference 1
Flight crew number	Three
Operations	Domestic and international
Aircraft maximum gross takeoff weight	327 000 lb
Fuel cost, domestic	$ .10 per gallon
Fuel cost, international	$ .11 per gallon
Fuel density	6.716 lb per gallon
Block fuel	As reference 1
Reserve fuel, domestic	As reference 1
Reserve fuel, international	As reference 1
Seats, total	149–30 first class/119 coach
Payload	Passengers: 205 lb each Cargo: none
Utilization	3800 hr per year

Where range considerations permitted, the cruise Mach number was assumed for minimum DOC to be 0.83 throughout the cruise. At maximum capacity payload range, a Mach number of 0.80 was assumed.

Airplane utilization was fixed at 3800 hr rather than assumed to vary with block time as stipulated by reference 1. A utilization of 3800 hr was considered to be representative of typical 707-320B operations.

Direct maintenance, flight equipment:

Labor rate	$5 per hour (25-percent increase over ref. 1)
Operating empty weight	Existing-nacelle airplane: 145 100 lb Treated-nacelle airplane: 148 240 lb
Material cost, airplane	As reference 1 plus 20 percent
Material cost, engine	As reference 1 plus 20 percent
Nacelle maintenance cost (per airplane)	Existing nacelle: $10.8 per flight hour Treated nacelle: $12.1 per flight hour
Airplane downtime due to retrofit	Zero

The operating empty weight assumed for the existing nacelle airplane is typical of the fully equipped standard commonly found in airline service. Due to the nacelle modifications, the estimated weight of the treated-nacelle airplane increases 3140 lb.

The estimated maintenance cost for the treated nacelle is based on a theoretical analysis of the nacelle previously described in volume IV, with the addition of a production thrust reverser installation. For the inlet, the additional costs of inspecting, cleaning, and repairing the treated areas were estimated. A lengthy service test under airline operating conditions would be required to substantiate the estimates. Treated-nacelle maintenance is more fully discussed in volume IV. The maintenance cost increase due to the treated nacelles is thus $1.3 per flight hour. This is to be compared with the total estimated airplane maintenance cost (1972 prices) of approximately $200 per flight hour.

It was assumed that the retrofit operation would be accomplished concurrently with a scheduled overhaul period and, therefore, no allowance was made for any additional out-of-service time.

Depreciation, flight equipment:

Depreciation period	Airplane: 12 yr Treated nacelles: 5 yr
Residual value	Zero

Spares holdings	Airframe, current configuration: 10 percent Treated nacelles: 20 percent Engines: 40 percent
Cost of retrofit	$1 000 000 (1972 prices)
Total initial airplane cost	$7 439 000
Cost of one engine	$283 000

The depreciation period for the airframe conforms to reference 1. The period for the treated nacelles was assumed to be 5 yr to reflect the fact that by 1972 the airplanes will be partly depreciated.

Spares holdings for the engines and airframe less treated nacelles conform to reference 1. Current experience shows that existing production nacelles require from 13 to 17 percent spares—spares that can be truly considered nacelle components and not engine components. Spares for the treated nacelles were assumed to be 20 percent to reflect this current experience and to add some conservatism with regard to the relative lack of operational experience with the treated nacelle.

There are many uncertainties in estimating retrofit cost, mainly with respect to production techniques for the polyimide-fiberglass acoustic material, date of go-ahead, number of kits produced, production rate, and the method of performing the installation in airline service. A possible production schedule is shown in figure 4. The schedule is based on a production rate of approximately 16 airplane sets (64 nacelles) per month and has been chosen to match the requirement for the availability of kits at the 3-yr major overhaul periods. The first kit would be available for the certification program 19 mo after go-ahead. Certification of the 707-320B/C models should be accomplished 27 mo after go-ahead. On the basis of this schedule, the current estimate for the total price of retrofit (including installation) is shown in figure 5. It will be seen that for total numbers of ship sets exceeding about 300, the retrofit price becomes $1 million. The total number of 707-320B/C models delivered or on order currently exceeds 420 airplanes. With the 20-percent spares provisioning for all airplanes (domestic and foreign airlines), the total requirement would be about 500 ship sets.

Insurance:

Rate	2 percent, as reference 1
Insured value	$8 039 000

Indirect operating costs.—Table I summarizes the Boeing/Lockheed method, as revised by Boeing in 1967, used to calculate indirect operating costs. An analysis of 1968 costs of four large carriers showed 49 and 6 percent of total indirect operating costs were due to labor and material, respectively. If by 1972 these costs are assumed to escalate 25 and 20 percent, respectively (as assumed for direct operating costs), the total indirect operating cost would increase by 13.5 percent. This increase was applied to estimates obtained from table I.

Items that could be affected by the nacelle acoustic modifications are:

- Aircraft servicing
- Servicing administration
- Maintenance on ground equipment
- Depreciation and amortization of ground equipment costs

It is believed that these five items are unlikely to escalate with incorporation of the nacelle modifications, as implied by the simple formulas of table I. For example, the discussion on treated-nacelle maintenance in volume IV indicates the possible need for additional washing equipment and, perhaps, special repair facilities for new materials used in the acoustic linings. However, it is considered that the maintenance, depreciation, and amortization of such items will be negligible compared with a cost assumed to be proportional to that of the flight equipment. Nonetheless, these items were briefly studied in an attempt to assess possible cost increases realistically. A conservative estimate produced an increase of less than $1 per airplane trip, compared with total indirect operating costs for a typical international stage estimated to be about $4000 per trip.

The ground rules of table I were therefore assumed for the existing-nacelle airplane. Changes of indirect operating costs indicated by these formulas due to nacelle modifications were ignored. Indirect operating costs were thus assumed to be the same for both the treated- and existing-nacelle airplanes.

Direct Operating Costs

Domest performance was calculated from flight data and shows a range loss of approximately 200 n. mi. at the seat-limited passenger payload (fig. 6). Of this loss, 160 n. mi. can be attributed to the fuel displaced by the increased operating empty weight. The remainder is due to the reduction of fuel mileage (nautical air miles per pound of fuel). The effects on block fuel and block time were also determined and found to be slight (fig. 7). In these respects, the JT3D-3B and JT3D-7 powered airplanes are identical.

The resulting direct operating costs for the existing- and treated-nacelle airplanes are shown in figure 8. The increase in direct operating cost for the treated-nacelle airplane is shown in figure 9. The percentage increase due to nacelle modifications is about 9.6 percent. A breakdown of direct operating costs into the various source elements for both airplanes shows the greatest difference between the two to be due to the depreciation factor (fig. 10). At the CAB distance considered (1000 n. mi.), the following elements contribute to the total increase:

	Percent of total increase
Crew pay	0
Fuel	8.1
Insurance	5.1
Maintenance	2.1
Depreciation	84.7
	100.0

In determining the increase of DOC due to the nacelle modifications, the retrofit price, nacelle spares provisioning, and depreciation period for the nacelle thus become the main determining items.

International operations.—The effect of the nacelle modifications on payload-range performance in international operations shows a range loss of 200 n. mi. (fig. 11). Of this loss, 160 n. mi. is attributable to the fuel displaced by the increased operating empty weight. The effect on block fuel and block time is shown in figure 12.

The resulting direct operating costs are shown in figure 13. The percentage increase in DOC due to the nacelle modifications is about 9.2 percent (fig. 9) and, again, a breakdown of the costs into the various source elements shows that the greatest difference is incurred in cost due to depreciation (fig. 14). At 2500 n. mi., the following elements contribute to the total increase:

	Percent of total increase
Crew pay	0
Fuel	9.5
Insurance	4.8
Maintenance	1.8
Depreciation	83.9
	100.0

Indirect Operating Costs

Indirect operating costs are presented in figure 15 for domestic rules and in figure 16 for international rules. According to the assumptions made and discussed earlier, no change in indirect operating costs due to the nacelle modifications was assumed.

AIRLINE FLEET STUDY

Basic Methodology and Assumptions

General.—The objective of this part of the study was to theoretically model an airline fleet operation and to assess the effects that a treated-nacelle retrofit program would have on the operational and economic parameters. The results of the flight tests previously described (vol. IV) were used wherever possible. This involved translating the performance and acoustic changes due to the treated nacelles from the JT3D-7 engine of the test airplane to the JT3D-3B engine of this study.

With regard to performance, only takeoff distance and climbout performance are affected by the engine change. When both parameters were calculated for the existing-nacelle airplane, they agreed closely with the flight test results. The JT3D-3B engine requires a smaller air mass-flow than the JT3D-7 engine at takeoff rating. From the data of volume IV, it was possible to calculate the reduced thrust loss due to nacelle treatment for the JT3D-3B engine. This difference was computed to arrive at the required takeoff performance with the JT3D-3B engines, both with and without the nacelle treatment.

With regard to noise levels, it has been assumed that at a given height and thrust, the airplane with JT3D-3B engines generates the same EPNL as the JT3D-7 variant, with or without the nacelle treatment. This has been confirmed for the existing nacelle by other Boeing flight tests.

The result of combining the performance differences and noise level data is shown in table II (thrust cutback corresponds to a climb gradient of 6 percent).

Airline simulation.—Airline simulation was effected through a Boeing computer program called the Airplane Economic Design Evaluator (AEDE). A data flow diagram for the computing system is shown in figure 17. The program, as applied to this particular task, is discussed in detail in the appendix. In brief, it simulates a fleet operation over a chosen route network, with statistical descriptions of passenger demand and airfield temperature conditions included. The computer program leads to realistic operations in which the airplanes are occasionally unable to accept the full demand either as a result of capacity restrictions or performance restrictions. Since the choice of passenger demand, along with airfield and route weather data, is obviously of primary importance, the present study was done for two quarters of the year, summer and winter.

Route system.—The route system chosen is illustrated in figure 18. It represents very closely the external systems of two actual airlines, one serving Hawaii and the other serving Europe, Africa, and the Middle and the Far East. Tables III and IV summarize the pertinent mileage, geographical, and meteorological data used in the analysis for the summer and winter quarters.

Passenger demand.—The assumed average passenger demand between each city pair for the two annual quarters is given in table IV. These numbers correspond to the average load factors actually achieved in the years 1967 and 1968:

	Summer	Winter
U.S. to Hawaii	61.0	50.2
U.S. through routes		
—from Hawaii	61.0	50.2
—from transatlantic	55.1	41.0
Transatlantic	64.6	46.9
Fifth freedom	43.0	31.0

The passenger demand distribution was assumed to be a normal frequency distribution with a standard deviation from the mean given by 0.515 times average passenger demand per trip. This has been found to be representative of current operations.

Airline flight operations.—An annual average utilization of 3785 hr was assumed for the basic unmodified airplane. Note that the utilization is approximately the same as that used previously in studying direct operating costs. The slight difference is due to the obvious need to have a whole number of airplanes in the fleet study. This average utilization led to a requirement of 115 airplanes for the route system described previously. The 115-airplane fleet size was assumed to be held constant throughout the retrofit process. Had service level shown to be appreciably affected by the nacelle modifications, it might have been necessary to revise the assumption of a given fleet size. As will be seen from the results of the study, this did not prove to be the case.

Where possible, fuel requirements were assumed to be according to minimum-cost flight techniques: that is, a cruise Mach number of 0.83 was used. However, where a city pair was shown to involve too large a stage length for the worst applicable conditions of wind and temperature, maximum-range flight techniques were used; i.e., a cruise Mach number of 0.80 was employed.

With regard to the operational noise data, thrust cutback during climbout to produce a climb gradient of 6 percent was assumed. Thrust cutback was used only at altitudes above the airfield of 700 ft or more.

The airplane maximum gross weights were 327 000 and 207 000 lb for takeoff and landing, respectively.

Airline economic treatment.—Where possible, costs were calculated in a similar manner to those of the previously discussed direct and indirect operating costs. However, costs were computed individually for each trip and thus properly reflect the effects of wind, airfield temperature, and load factor. As before, costs were escalated to a forecast 1972 level, and the total price of a retrofit was assumed to be $1 million.

Passenger yield was assumed to follow the pattern illustrated in figure 19. This estimate was obtained by taking revenue data for 12 U.S. scheduled carriers from the CAB traffic and financial statistics over 6 consecutive years. These data were obtained for four separate categories—domestic coach, domestic first class, international coach, and international first class. It was found that when the data were suitably weighted to reflect the individual airline sample size, the yield for any given year could be expressed in the form:

$$\log \text{yield} = F + G\ (\log \text{CAB distance})$$

where yield is in cents per passenger mile and F and G are empirically selected constants for each particular year. The data shown in figure 19 are for 1968. It was not considered appropriate, or a valid use of the yield analysis, to predict passenger yield for the year 1972.

Figures of profit and return on revenue produced by this study should therefore be closely identified with the important provisos:

- Operating costs estimated as for 1972
- Passenger yield as for 1968
- Passenger revenue only (no cargo or other revenue)
- Route system and passenger demand as for 1968

Results

Airplane flight operations.—Figure 20 shows the percentage of flight frequency distribution as a function of stage length for the fleet operations of each airplane. This figure reflects the assumptions made with regard to passenger demand and route system. Note that the peak trip frequency lies in the 2000 to 2250 n. mi. band of CAB distance. The maximum CAB distance required is in the 4500 to 4750 n. mi. band and represents one city pair only: London and Los Angeles.

Table V compares the main operational quantities for the airplanes with and without the nacelle modifications. The figures are averages for the summer and winter quarters. The significance of table V is that an extra 68 passenger denials are incurred with the treated-nacelle airplane, subtracting from the original 127 963 passengers carried per week. These extra denials occur on the five longest westbound flights and are due mostly to the reduction of capacity payload range suffered by the airplane with treated nacelles. It follows, therefore, that a route system with a higher proportion of long-range flights, higher load factors, or the additional carriage of cargo will incur a greater number of passenger denials.

Airplane noise levels.—The frequency distribution of noise level experience at the measuring points prescribed by reference 2 was deduced for the fleet operation studied. Reflected, therefore, are the variation of takeoff and landing weights to achieve the stage length distribution of figure 20 and also the variation of airfield temperature, which affects the climbout profile. The effect of ambient temperature on noise radiation was believed to have a minor effect on the final noise distribution and, for the purposes of this part of the study, was neglected. The airplane noise levels used are consistent with those reported in volume IV.

Figure 21 shows the landing approach noise level distribution collected in 3-EPNdB bandwidths. It can be seen that because of the small variation in landing weight throughout the annual fleet operation, 100 percent of the total landing noise experiences fall in one bandwidth for each configuration, i.e., 117 to 120 EPNdB for the existing nacelle and 102 to 105 EPNdB for the treated nacelle.

Figure 22 shows the takeoff noise level distribution collected in 5-EPNdB bandwidths. Because of the wide spread of takeoff weights, the noise levels are distributed over a wide range of EPNL. No estimates are shown below 85 EPNdB because of lack of test data at the low EPNL. Thrust cutback to provide a 6-percent climb gradient has been assumed for altitudes not less than 700 ft above the airfield. Figure 22 shows that the frequency of noise level experience above 100 EPNdB is reduced from 40 percent of the total number of flights to 13 percent. Noise level experience above 110 EPNdB is reduced from 4 to 0 percent. Such reductions of frequency may be quite significant to the areas surrounding main international service airports where most of the long-range flights originate.

Economic comparison.—A comparison of the economic quantities for the two fleet operations is presented in table VI. The passenger revenue earned is reduced by 0.10 percent. This loss is due to the 68 fewer passengers carried (table V) and therefore concerns the long-haul content of the network. Direct operating cost increases by 9.4 percent, which, when compared with the increases indicated by figure 9 (generally about 9.6 and 9.2 percent for domestic and international operations, respectively), reflects the mixture of domestic and international costs involved in the route system of this particular study.

As a consequence of the increased direct operating cost (indirect operating cost is assumed to be unchanged), the return on passenger revenue is reduced by 4.3 percent. A 4.3-percent increase of passenger yield would be required to restore the dollar operating profit existing before the nacelle retrofit was effected (the operating profit in this study being based solely on passenger revenue). A still higher increase would be required to secure a given percentage return on the higher investment brought about by the nacelle modifications.

In interpreting these results, two points need to be emphasized. First, the maximum stage length for the route system studied falls in the range from 4500 to 4750 n. mi. The fleet operation of this hypothetical study was not greatly affected by the reduction of capacity payload range due to the treated nacelles. A system with a higher content of long-range routes or higher overall load factors (including cargo) would demonstrate a greater sensitivity to the nacelle modifications and would undoubtedly show a greater economic penalty. Second, for the purpose of estimating operating costs for the year 1972, the assumption has been made that the complete fleet of 115 airplanes will be retrofitted. The price estimate for retrofit has assumed that the retrofit will occur concurrently with normal overhaul periods to minimize airplane out-of-service times. Consequently, retrofit operations will be spread over a period of time greater than 1 yr. The production schedule of figure 4 also indicates that it will not be possible to retrofit all Boeing 707-320B/C models by the end of 1972. The cost implications of a slide in retrofit scheduled beyond 1972 must be evaluated to reflect each individual airline route system and retrofit schedule.

CONCLUDING REMARKS

The operational and economic impact of nacelle modifications to reduce airplane noise has been studied for the Boeing 707-320B powered with Pratt & Whitney JT3D-3B engines. The modifications comprise a two-ring treated inlet and a full-length treated fan duct. The increase of airplane operating empty weight would be 3140 lb, which leads to the major effect on performance—a capacity payload range loss of approximately 200 n. mi. due to the available fuel displaced.

The major economic effects of the above changes are as follows:

- A total installed retrofit cost of $1 million based on a production run of approximately 300 or more airplane sets.

- A 9.2-percent increase of international direct operating cost, due mainly to the treated-nacelle depreciation. In this study, the depreciation period of the treated nacelle has been assumed to be 5 yr.

- A reduction of revenue-earning capacity for the airline route structure and stage-length distribution assumed in this study. The revenue loss would increase for a route structure with a higher content of long-range stages, higher passenger load factor, or the additional carriage of cargo.

- A 4.3-percent reduction in return on revenue for the case considered. In a narrow-margin industry like the airline industry, such an apparently small reduction in return can have a drastic impact on profitability.

The major operational effects of the nacelle modifications are:

- A loss in the available airplane load carrying capacity at stage lengths beyond about 4250 n. mi., particularly on westbound flights. This loss would increase for a route structure with a higher content of long-range stages.

- A uniform reduction of noise level for all landings by about 15 EPNdB.

- Some reduction of the frequency of high noise levels at takeoff. For instance, the frequency of noise levels above 100 EPNdB at the 3.5 n. mi. point would be reduced from 40 percent of the total flights to 13 percent.

Further work is necessary in the following areas:

- Validation of retrofit price estimates, particularly as affected by design and production techniques for polyimide-fiberglass acoustic panels.

- Validation of in-service performance of the acoustic panels and the associated maintenance cost.

- Consideration of the cost effects of a retrofit schedule extending beyond 1972.

- Consideration of the case of an airline route system with a higher content of very long-range stages and higher load factors, including the carriage of cargo.

- Consideration of cargo operations with higher payloads as permitted by the Boeing 707-320C airplane.

The Boeing Company
Commercial Airplane Group
Seattle, Washington, September 1969

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APPENDIX

AIRPLANE ECONOMIC DESIGN EVALUATOR (AEDE)

Introduction

The AEDE model was developed by the Operations Research/Management Sciences organization of the Commercial Airplane Group of The Boeing Company under the sponsorship of the technology staff. The project was started in November 1967 and a working model of AEDE was first available in the fall of 1968.

The original objective of the AEDE model was to compare economic evaluations of alternate aircraft performance designs competing over the same carrier's route network. Thus, it was felt that AEDE was well suited to investigate the impact of nacelle modifications to basic aircraft designs.

Part I of the AEDE program takes a well-defined set of city pairs and simulates the interaction of given random passenger demand and random takeoff airport temperature with the aircraft performance description to obtain estimates of time, fuel, and service level indicated by the number of passenger denials. Where aircraft performance was limited by noise considerations, the AEDE model increases frequencies and reduces load factor to bring the service level back to the same number of passengers per week. Thus, passengers carried can be thought of as the true demand for service, and passengers denied from other flights can be considered as part of the input demand for the given flight. This assumes that, on the average, demand for the given flight coming as denials from other flights is equal to the average denials generated by the given flight.

Part 2 of the AEDE system applies economic inputs to the results of Part 1 and computes financial figures of merit for each aircraft.

Part 1, Basic Operating Facts

The purpose of Part 1 of the AEDE program is to compute basic operating facts of each aircraft separately over each of the carrier's city pair legs. The main inputs for each leg are:

- Random distribution of passenger demand
- Random distribution of temperature of the takeoff runway at flight departure time
- City pair distance and average enroute winds

- Trip frequencies (trips per week)
- Takeoff runway elevation and length
- Aircraft performance description:
  - Takeoff performance charts (maximum gross takeoff weight as a function of runway temperature, elevation, and length)
  - Fuel consumption versus payload, and flight hours at minimum cost and long range cruise conditions
  - Fuel reserves and allowances
  - Operating empty weight

The outputs of Part 1 of AEDE are called basic operating facts (per trip and per week for each city pair leg):

- Flight hours
- Block hours
- Fuel burned
- Average capacity offloads (denials)
- Average performance offloads (denials)
- Average number of passengers carried

Weekly route system totals for each aircraft (input to Part 2) are obtained by adding weekly city pair values.

Passenger demand.—Average passenger demand per trip μ is input to AEDE for each city pair. The AEDE model then assumes a normally distributed passenger demand with mean μ, and standard deviation $\sigma = Q\mu$, where Q is also an input parameter. Experience with empirical modeling of various route systems has shown this method of estimating σ to be quite realistic. Empirically if μ is specified separately for each city pair, the value of Q should be 0.383. If μ is the average passenger demand for the whole system, the value of Q is 0.515.

Fuels and payload capability.—For a fixed range, AEDE will determine the fuel and payload capability by solving the following simple relationship for H:

$$W = H + E_W + X_f + F(H) + S(H) \tag{A1}$$

where:

E_W = operating empty weight of the aircraft, lb

T = runway temperature, °F

W = the aircraft gross takeoff weight corresponding to a payload demand H for a given range, lb

X_f = fuel allowance for taxi-in after touchdown, lb

H_P = weight of a full passenger payload, lb

H = passenger payload weight demand, lb

F(H) = fuel burned in flight + air maneuver, lb

S(H) = reserve fuel required on board, lb

S(H) and F(H) are direct functions of payload

The solution requires an iteration because the fuel burned and reserve fuel are a function of payload. When

$$W = W^*(T),$$

then

$$H = H^*(T)$$

where:

$H^*(T)$ = maximum payload capacity (lb) at runway temperature T ($H^*(T)$ also depends on flight cruise conditions and city pair range.)

$W^*(T)$ = maximum gross takeoff weight, a function of T and the takeoff runway length and altitude (this relationship is provided to the AEDE program by tables containing the performance takeoff data)

Criticality test.—For each city pair, AEDE applies equation (A1) to determine whether the aircraft can take off with a full passenger payload H_P on a prescribed high-percentile (e.g., 95 percent) hot day T with a prescribed extra headwind (e.g., 25 kn) flying a minimum cost cruise schedule. If it can, the city pair is classified as noncritical, and minimum cost fuel will be used in all subsequent calculations involving F(H) and S(H) (minimum cost flight times will also be used). If it cannot, the long-range cruise fuel and block times will be used.

W*(T) is computed from the aircraft takeoff performance charts for T set at 95 percent of the temperature probability distribution, and H_P is used in equation (A1) to obtain the required gross takeoff weight W_P. If W_P exceeds W*(T), the city pair becomes "critical." Otherwise it is "not critical."

Passenger denials.—Let H(T) = min (H*(T), H_P), where H*(T) and H_P were previously defined as maximum payload weight capability and the weight of a full passenger payload, respectively. H(T) is a random variable because T is.

Total passenger denials J occur whenever demand H exceed H(T). Total denials include capacity denials J_C which occur whenever H exceeds H_P. Performance denials are computed as their difference, J - J_C.

Capacity denials depend on the single random variable H. Performance denials depend on two random variables T and H. AEDE computes expected denials per trip as follows:

Let $F_H(h)$ be the distribution function of H. $F_H(h)$ is completely determined by the mean of H and μ, since AEDE uses $\sigma = Q\mu$ and treats H as being normally distributed. The formula for computing expected capacity offloads is:

$$J_C = \int_{H_P}^{\infty} (h - H_P) dF_H(h) \qquad \text{(A2)}$$

which is independent of temperature.

Again using H(T) = min (H*(T), H_P), total expected offloads are computed as:

$$J(T) = \int_{\overline{H}(T)}^{\infty} [(h - \overline{H}(T)]\ dF_H(h) \qquad \text{(A3)}$$

Expected performance offloads are computed as:

$$J_P(T) = J(T) - J_C \qquad \text{(A4)}$$

Of course, if maximum gross weight H*(T) exceeds H_P, then $J(T) = J_C$ and $J_P(T) = 0$.

Although expected capacity denials per trip are given unconditionally by equation (A2), performance denials in equation (4) are conditional upon random denial temperature T. To obtain an unconditional expected performance denial, AEDE approximates the cumulative denial temperature distribution at the origin city by N discrete temperatures T_i and associated probabilities P_i. AEDE then computes $J_P(T_i)$ for each T_i and applies the associated probabilities to obtain

$$E_W(J) = \sum_{i=1}^{N} P_i J_P (T_i) \qquad \text{(A5)}$$

as the unconditional expected performance denials.

Target service level.–If desired, AEDE will factor the passenger demand and trip frequency to attain a prespecified target service level for each city pair separately. Target level is in the form of "weighted denials," which can be a weighting of one fare per passenger denial. The major impact is felt in the increase in weekly block hours, which of course increases initial investment in aircraft as well as in operating costs.

Number of aircraft required.– Throughout the study, number of aircraft required to service a given route system N was computed from average aircraft utilization U_A (block hours per day per aircraft) and total fleet block hours per day B as follows:

$$N = B/U_A$$

Average utilization was estimated for each system using average block hours per trip and ATA conversion tables can be used(Ref. 1) to obtain practical values of airplane utilization. However, in this study the assumed number of airplanes in the fleet was varied until an average utilization of approximately 3800 hr per annum was achieved.

Part 2, Economic Evaluation

This part of AEDE uses the airplane operational data generated by Part I and assumed economic data to calculate revenue and costs. The results of Parts I and 2 form the AEDE output that can be compared with corresponding results from another configuration.

The revenue and costs are calculated as shown below.

$$\text{Revenue} = \sum_{\substack{\text{Route} \\ \text{system}}} (\text{Fare x Frequency x Passenger payload/passenger weight})$$

$$\begin{aligned} \text{Total operating costs} = \sum_{\substack{\text{Route} \\ \text{system}}} & \{[(\text{Flight hour dependent costs x flight time}) \\ & + (\text{Block hour dependent costs x block time}) \\ & + (\text{Fuel cost x Fuel burned}) \\ & + (\text{Flight cycle dependent costs})] \text{ x Frequency}\} \\ & + (\text{Insurance rate x Airplane cost x number of airplanes}) \end{aligned}$$

Indirect costs and any additional direct costs can be added to the above.

TABLE I.—BOEING METHOD FOR CALCULATING INDIRECT OPERATING COSTS[a]

		C: Domestic	C: International
Passenger service			
Cabin attendants — Domestic	$C\left(\frac{\text{Coach seats}}{40}+\frac{\text{FC}^{b}\text{ seats}}{20}\right)$ (Block hours)	9.00	
Cabin attendants — International	$C\left(\frac{\text{Coach seats}}{30}+\frac{\text{FC seats}}{15}\right)$ (Block hours)		12.00
Passenger food — Domestic	[0.60 + 0.30 (Block hours)] [(Coach seats) (LF[c]) + (2.00) (FC seats) (LF)]		
Passenger food — International	[0.75 + 0.32 (Block hours)] [(Coach seats) (LF) + (3.00) (FC seats) (LF)]		
Other passenger service	C [(Coach seats) (LF) + (FC seats) (LF)] x (Flight distance, statute miles)	0.0013	0.0020
Aircraft servicing			
Aircraft control	C (Departure)	17.10	62.40
Aircraft servicing	$C\left(\frac{\text{Maximum gross weight, lb}}{1000}\right)$	0.59	1.44
Traffic servicing			
Passenger handling	C [(Coach seats) (LF) + (FC seats) (LF)] x (Enplaned to onboard ratio)	1.60	3.60
Cargo and baggage handling	C [(Tons baggage) (Enplaned to onboard ratio)] + [(Terminal labor cost per ton)[d] (Tons mail, express, and freight) (Enplaned to onboard ratio) (0.75)]	50.00	60.00
Servicing administration			
	C (Aircraft servicing expense and traffic servicing expense)	0.093	0.093
Reservations and sales			
Reservations and sales	C [(Coach seats) (LF) + (FC seats) (LF)] x (Enplaned to onboard ratio)	2.60	7.80
Passenger commissions	C [(Coach seats) (LF) + (FC seats) (LF)] x (Flight distance, statute miles)	0.0011	0.0030

TABLE I.—BOEING METHOD FOR CALCULATING INDIRECT OPERATING COSTS—Concluded

		C	
		Domestic	International
Advertising and publicity			
Passenger	C [(Coach seats) (LF) + (FC seats) (LF)] x (Flight distance, statute miles)	0.0019	0.0028
Freight	C (Tons freight) (Flight distance, miles)	0.0063	0.0079
Ground Equipment			
Maintenance	C (Total direct maintenance, flight equipment)	0.095	0.095
Depreciation	C (Depreciation, flight equipment)	0.122	0.122
Amortization			
	C (Depreciation, flight equipment)	0.076	0.095
General and administrative			
	C (Total operating expense)[e]	0.043	0.054

[a]Results of indirect operating cost calculations in dollars per trip

[b]First class

[c]Load factor

[d]Terminal labor cost per ton:

$$\text{Piece weight under 2000 lb} = \frac{2000\,[1.10 + (0.58)\,(\text{Number pieces per shipment})]}{\text{Average shipment weight, lb}} + 10.00$$

$$\text{Piece weight over 2000 lb} = \frac{10.00 \times 2000}{\text{Average weight per piece, lb}}$$

Example:	Shipment weight	Av no. of pieces	Labor cost per ton
	200	5	$50.00
	400	8	38.70
	500	4	23.70
	1000	6	19.20

[e]Total operating expense = (Direct operating cost) + (Indirect operating cost - General and administrative)

TABLE II.—AIRPLANE PERFORMANCE COMPARISONS (Ambient Temperature 59°F)

Engine	Airplane takeoff weight, lb x 10^3	Takeoff distance to 35-ft height, ft		Height at 3.5 n. mi. from brake release, ft		Noise level at 3.5 n. mi. from brake release with thrust cutback, EPNdB	
		Existing nacelle	Treated nacelle	Existing nacelle	Treated nacelle	Existing nacelle	Treated nacelle
JT3D-7	330	8570	8720	1170	1050	113	108
JT3D-7	260	5270	5420	2310	2220	103	96
JT3D-3B	330	9220	9260	1000	900	114	109
JT3D-3B	260	5400	5440	2070	2010	104	97

TABLE III.—AIRFIELD DATA

City	City code	Runway length, ft	Runway altitude, ft	Temperature, °F (95 percent probability)[a]	
				Summer quarter[b]	Winter quarter[b]
Athens	ATH	10 495	90	97	65
Baltimore	BAL	9 450	146	91	60
Bangkok	BKK	10 525	12	94	98
Bombay	BOM	10 500	27	92	90
Boston	BOS	10 000	19	91	58
Cairo	CAI	10 827	366	99	80
Colombo	CMB	11 050	29	86	90
Denver	DEN	11 500	5331	92	62
Dharan	DHA	10 000	71	105	82
Detroit	DTW	10 500	639	92	54
Entebbe	EBB	9 875	3789	79	83
Frankfurt	FRA	12 800	368	85	56
Geneva	GVA	12 795	1411	87	57
Hong Kong	HKG	8 350	15	92	76
Honolulu	HNL	12 380	13	85	82
Washington, D.C.	IAD	11 500	313	95	68
Hilo	ITO	9 800	37	86	82
New York	JFK	14 572	12	92	59
Las Vegas	LAS	12 545	2171	108	70
Los Angeles	LAX	12 090	126	85	76
London	LHR	12 000	80	84	56
Lisbon	LIS	12 483	374	89	66
Madrid	MAD	13 451	1998	92	59
Milan	MXP	12 844	767	89	58
Nairobi	NBO	13 500	5327	73	79
Chicago	ORD	11 600	667	93	53
Paris	PAR	11 976	292	87	56
Philadelphia	PHL	9 491	14	92	58
Rome	ROM	12 795	6	91	64
San Francisco	SFO	10 600	11	83	67
Shannon	SNN	10 000	47	76	56
St. Louis	STL	10 018	571	99	62
Tripoli	TIP	7 306	263	98	76
Tel Aviv	TLV	9 974	131	98	77
Tunis	TUN	10 499	16	101	70
Zurich	ZRH	12 139	1416	87	57

[a]These temperatures will not be exceeded 95 percent of the time.

[b]Summer quarter: June, July, August
Winter quarter: December, January, February

TABLE IV.—AIRLINE ROUTE SYSTEMS DATA

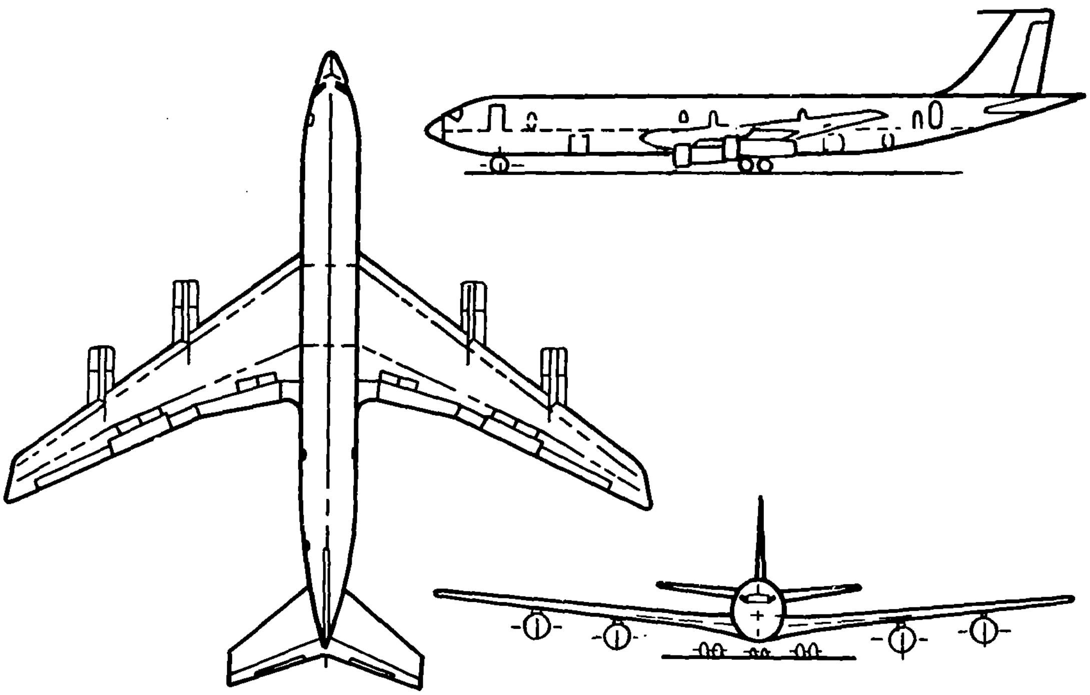
City pair	Range, n. mi.	Average wind, kn, tail wind positive				Average demand, passengers per trip		Trip frequency per week	
		Summer quarter		Winter quarter		Summer quarter	Winter quarter	Summer quarter	Winter quarter
		Eastbound	Westbound	Eastbound	Westbound				
HNL-ITO	188	0	0	0	0	91	75	28	18
SFO-ITO	2012	16	-17	20	-22			7	7
HNL-SFO	2086	17	-18	22	-24			35	35
ITO-LAX	2126	19	-19	23	-23			10	11
HNL-LAX	2223	18	-19	23	-25			45	45
HNL-ORD	3685	23	-25	30	-32			21	21
DTW-HNL	3885	23	-25	30	-32			7	7
BAL-HNL	4215	25	-26	34	-36			7	7
JFK-HNL	4327	26	-29	33	-36			7	7
BOS-HNL	4424	26	-29	33	-36			7	7
SFO-ORD	1604	30	-31	46	-49			52	52
JFK-LAX	2150	26	-27	55	-58			35	35
JFK-SFO	2248	30	-31	52	-55			31	31
BOS-SFO	2350	32	-34	51	-54	91	75	14	14
JFK-LHR	2990	32	-32	47	-47	96	70	28	14
IAD-LHR	3185	31	-31	47	-47			14	14
ORD-LHR	3423	27	-27	40	-40			14	14
LAX-LHR	4727	19	-19	23	-23			14	14
JFK-FRA	3340	31	-31	45	-45			14	14
JFK-PAR	3149	32	-32	47	-47			14	14
JFK-ROM	3705	31	-33	44	-47			28	14
JFK-ATH	4280	31	-31	44	-44			18	10
ORD-PAR	3599	28	-28	41	-41			14	6
JFK-MXP	3460	31	-31	45	-45	96		14	14
JFK-GVA	3346	—	—	46	-46	—		—	2
JFK-SNN	2670	33	-33	49	-49	96		14	6
JFK-MAD	3110	30	-30	44	-44			20	14
JFK-LIS	2917	29	-29	43	-43			16	12
BOS-LIS	2765	30	-30	42	-42	96	70	4	4
LHR-FRA	353	25	-25	26	-26	64	46	28	14
LHR-PAR	187	14	-14	28	-28			14	14
FRA-ZRH	155	-19	+19	-1	+ 1			14	14
ZRH-ATH	879	22	-22	23	-23			14	14
ATH-TLV	653	24	-24	41	-41			32	32
TVL-BOM	2183	51	-51	51	-51			14	14
BOM-BKK	1624	-14	+14	23	-23			10	10
BOM-CMB	824	-8	7	4	- 5			4	4
CMB-BKK	1286	-16	15	4	- 5			4	4
BKK-HKG	925	-12	12	35	-35		46	14	14
PAR-ROM	587	16	-16	—	—		—	14	—
ATH-EBB	2322	1	- 1	1	- 1		46	2	2
EBB-NBO	281	- 8	8	-20	20			2	2
NBO-PAR	370	- 5	5	4	- 4			2	2
ROM-ATH	578	29	-29	25	-25			28	28
MAD-ROM	717	29	-29	17	-17			14	20
LIS-MAD	277	25	-25	15	-15			14	14
ATH-CAI	602	17	-17	33	-33			6	6
CAI-DHA	1017	9	- 9	51	-51			6	6
MAD-TUN	681	25	-25	24	-24			2	2
TUN-TIP	289	-9	+ 9	-23	+23	64	46	2	2
ORD-LAX	1512	27	-27	50	-50	82	61	14	14
IAD-STL	603	26	-26	72	-72			14	14
STL-DEN	677	29	-29	55	-55			14	14
DEN-SFO	828	28	-28	44	-44	82		14	14
DEN-JFK	1419	—	—	61	-61	—		—	14
JFK-LAS	1948	—	—	59	-59	—		—	14
SFO-LAX	295	7	- 7	30	-30	82		14	14
JFK-SFO	2240	31	-31	55	-55			14	14
JFK-LAX	2144	27	-27	58	-58			28	28
PHL-LAX	2081	26	-26	59	-59			14	14
ORD-SFO	1600	31	-31	49	-49	82	61	14	14

TABLE V.—OPERATIONAL COMPARISON OF FLEET OPERATION

Quantity	Airplane	
	Existing nacelle	Treated nacelle
Average trips/week	1 753	1 753
Utilization hours/year	3 785	3 786
Average number of passengers/week	127 963	127 895
Average load factor, percent	48.99	48.97

TABLE VI.—ECONOMIC COMPARISON OF FLEET OPERATION

Quantity	Airplane		Change due to nacelle treatment, percent
	Existing nacelle	Treated nacelle	
Passenger revenue, average dollars/week	14 604 303	14 589 203	-0.10
Costs, average dollars/week			
Direct operating	6 509 095	7 119 039	+9.4
Indirect operating	7 759 654	7 759 654	0
Total operating	14 268 749	14 878 693	+4.3
Return on passenger revenue, percent	+2.3	-2.0	-4.3



Dimensions

Body length.................145 ft, 6 in.
Wingspan.....................145 ft, 9 in.
Wing sweepback........... 35°
Horizontal tail span......45 ft, 9 in.

Engines

Pratt & Whitney JT3D-3B turbofan

FIGURE 1.—BOEING 707-320B—THREE-VIEW GENERAL ARRANGEMENT

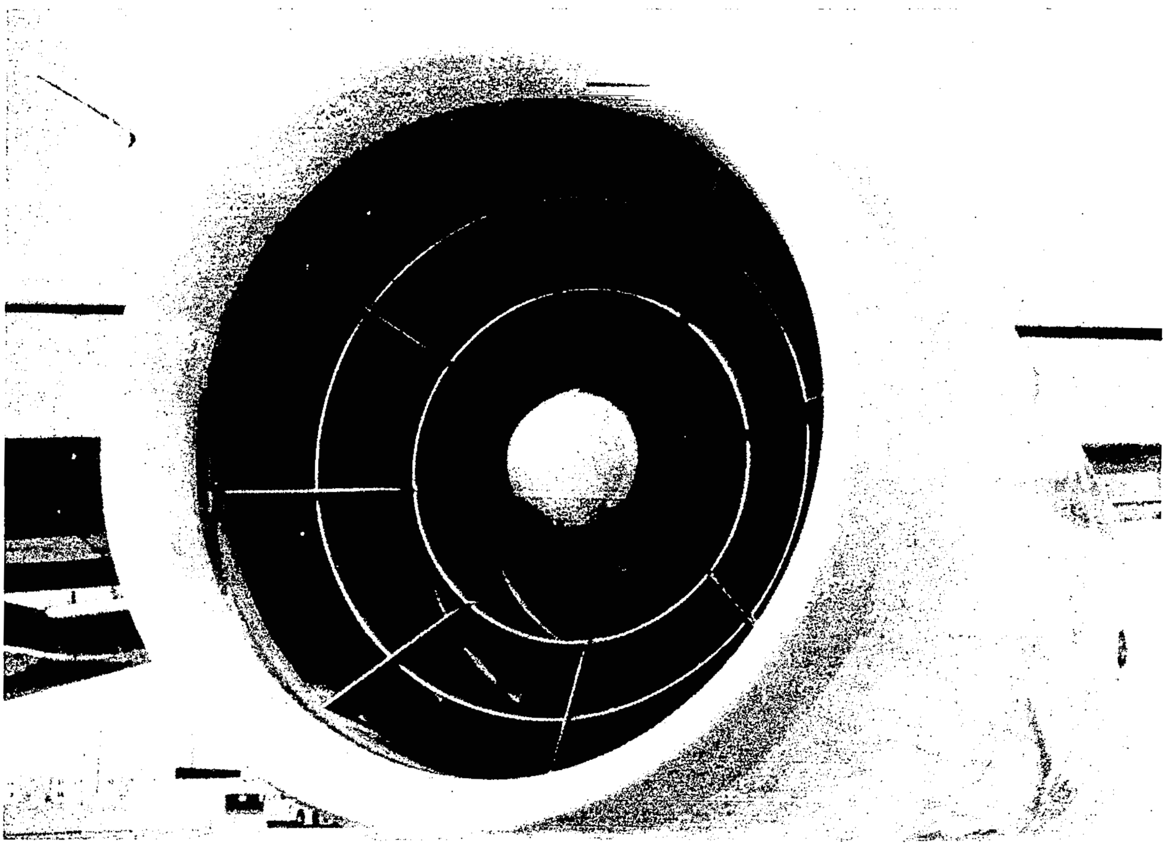


FIGURE 2.—TREATED NACELLE INSTALLED ON 707-320C AIRPLANE, FRONT VIEW

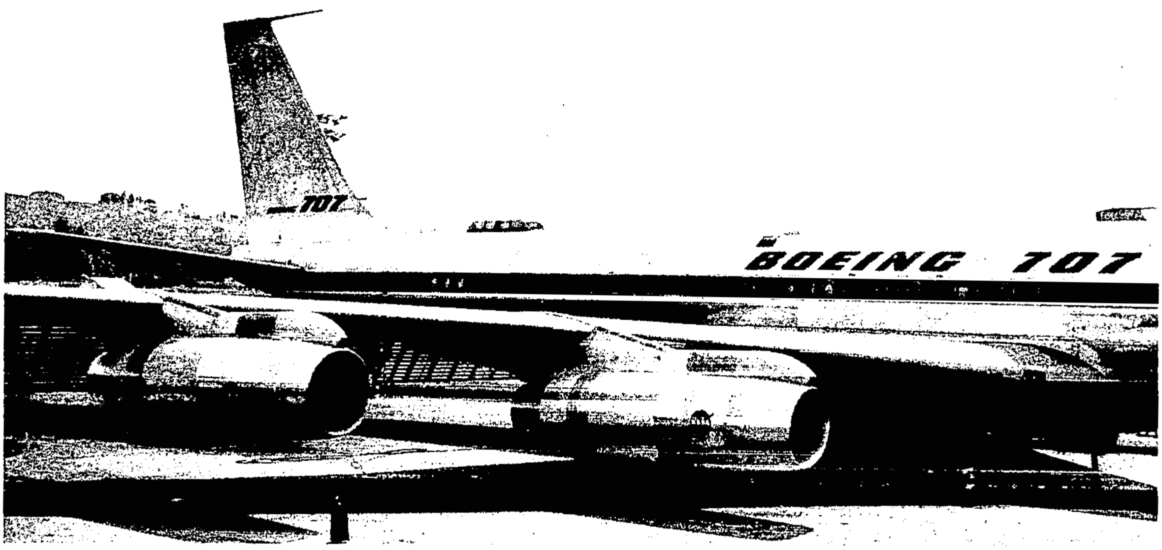


FIGURE 3.—TREATED NACELLE INSTALLED 707-320C AIRPLANE, SIDE VIEW

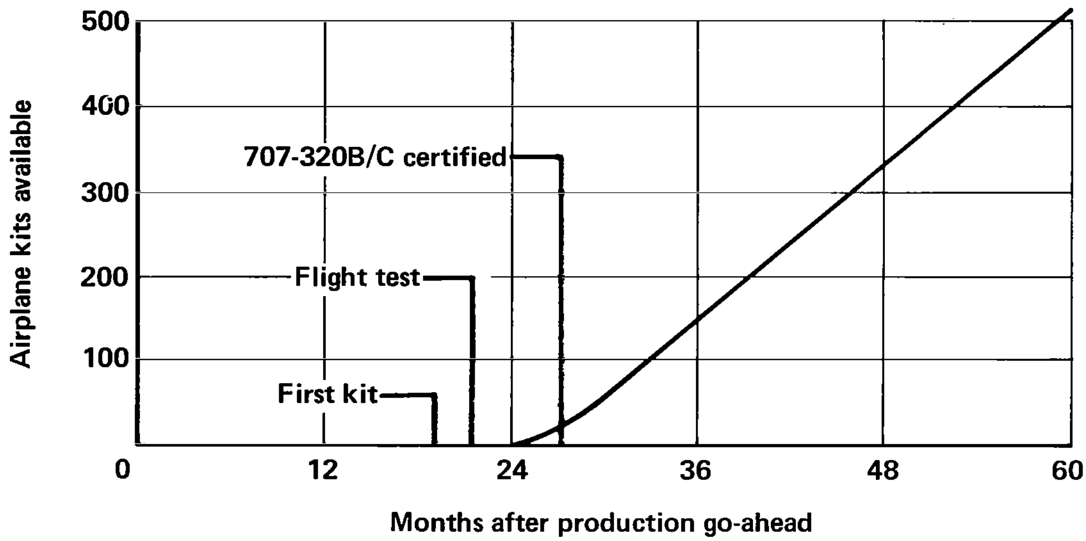


FIGURE 4.—RETROFIT KIT PRODUCTION SCHEDULE

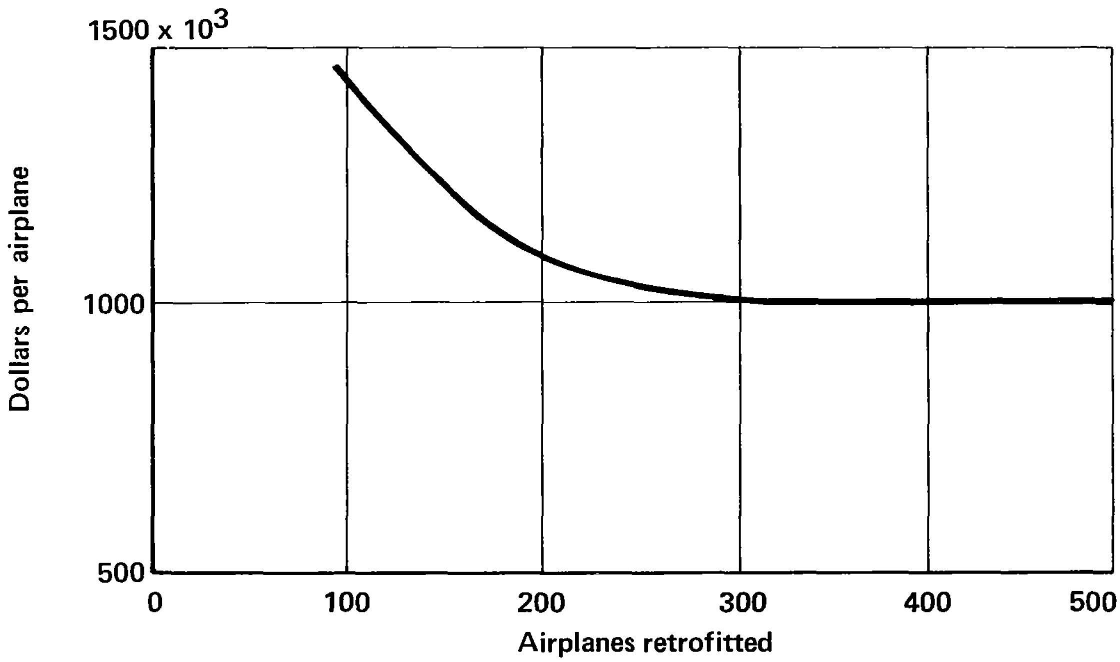


FIGURE 5.—RETROFIT PRICE

Weight	Existing nacelle	Treated nacelle
Max. gross takeoff weight, lb	327 000	327 000
Operating empty weight, lb	145 100	148 240
Max. zero fuel weight, lb	190 000	193 140

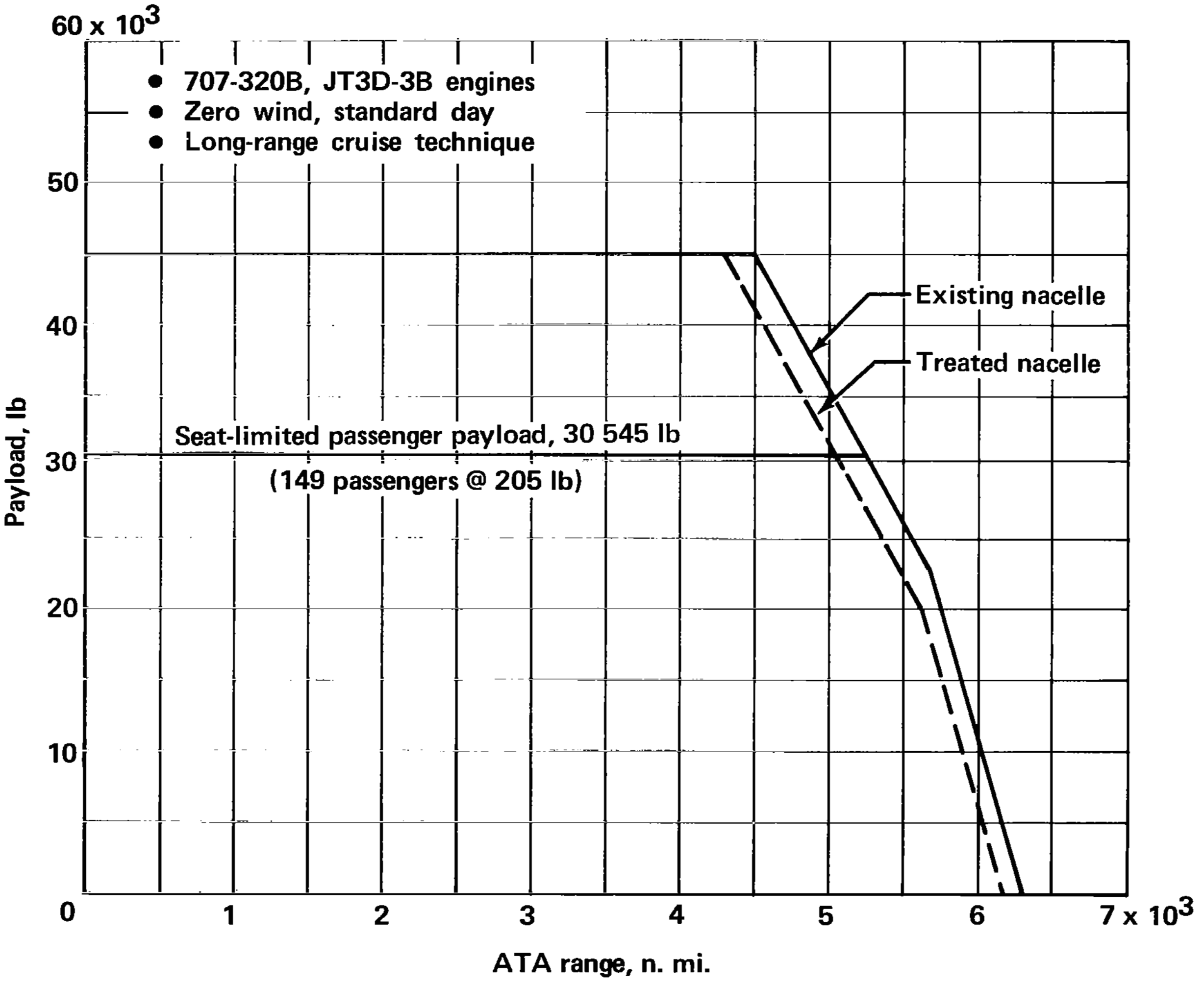


FIGURE 6.—ATA DOMESTIC RANGE PERFORMANCE

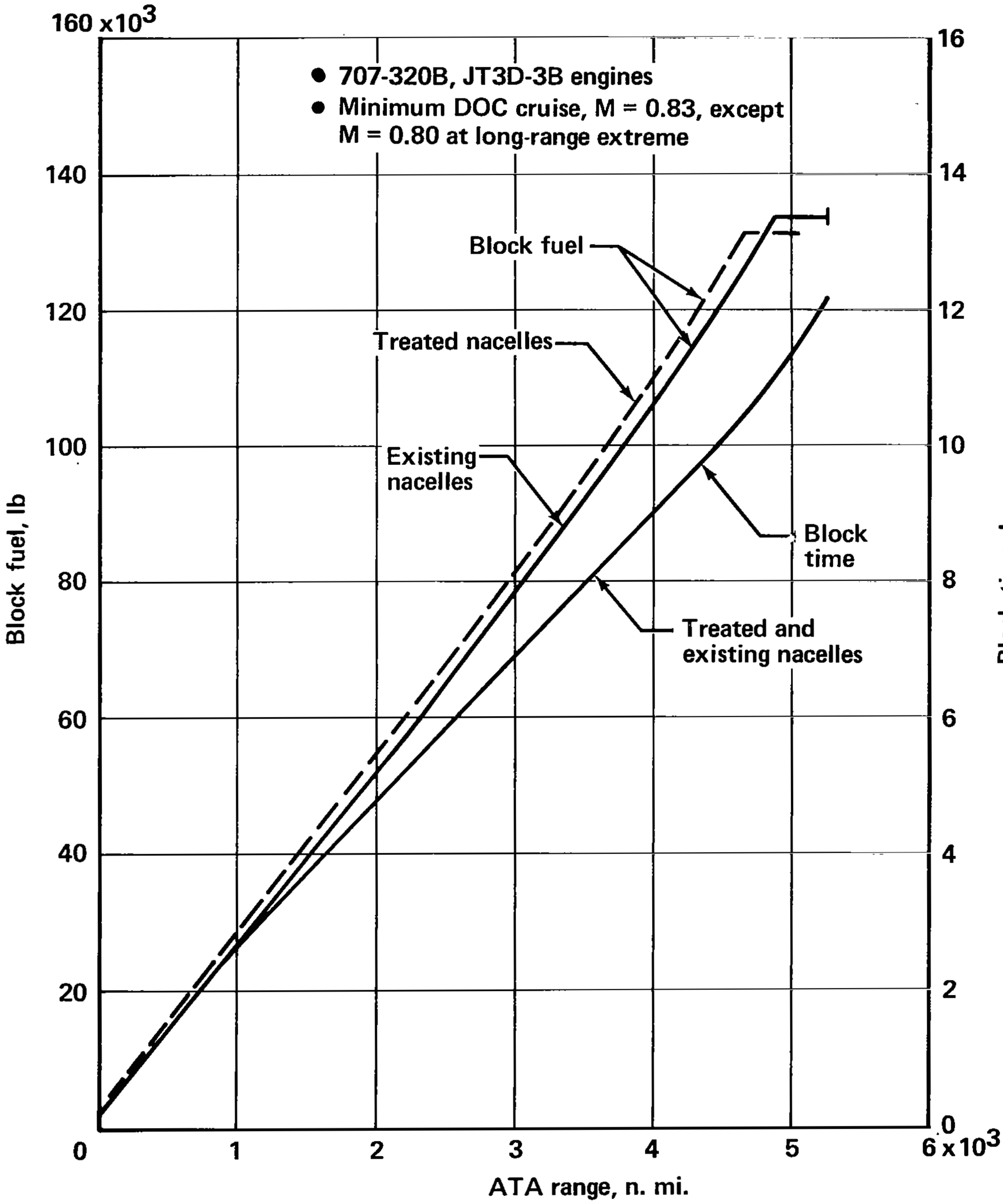


FIGURE 7.—ATA DOMESTIC BLOCK TIME AND FUEL

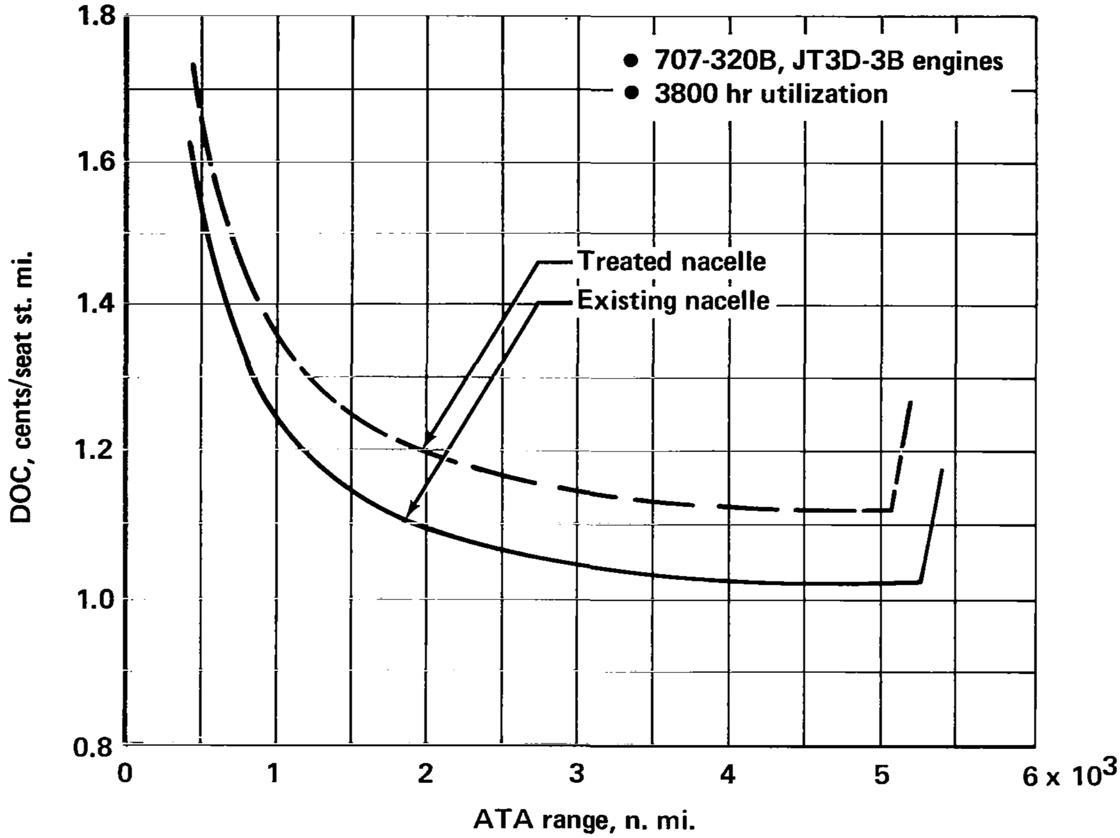


FIGURE 8.—ATA DOMESTIC DIRECT OPERATING COSTS

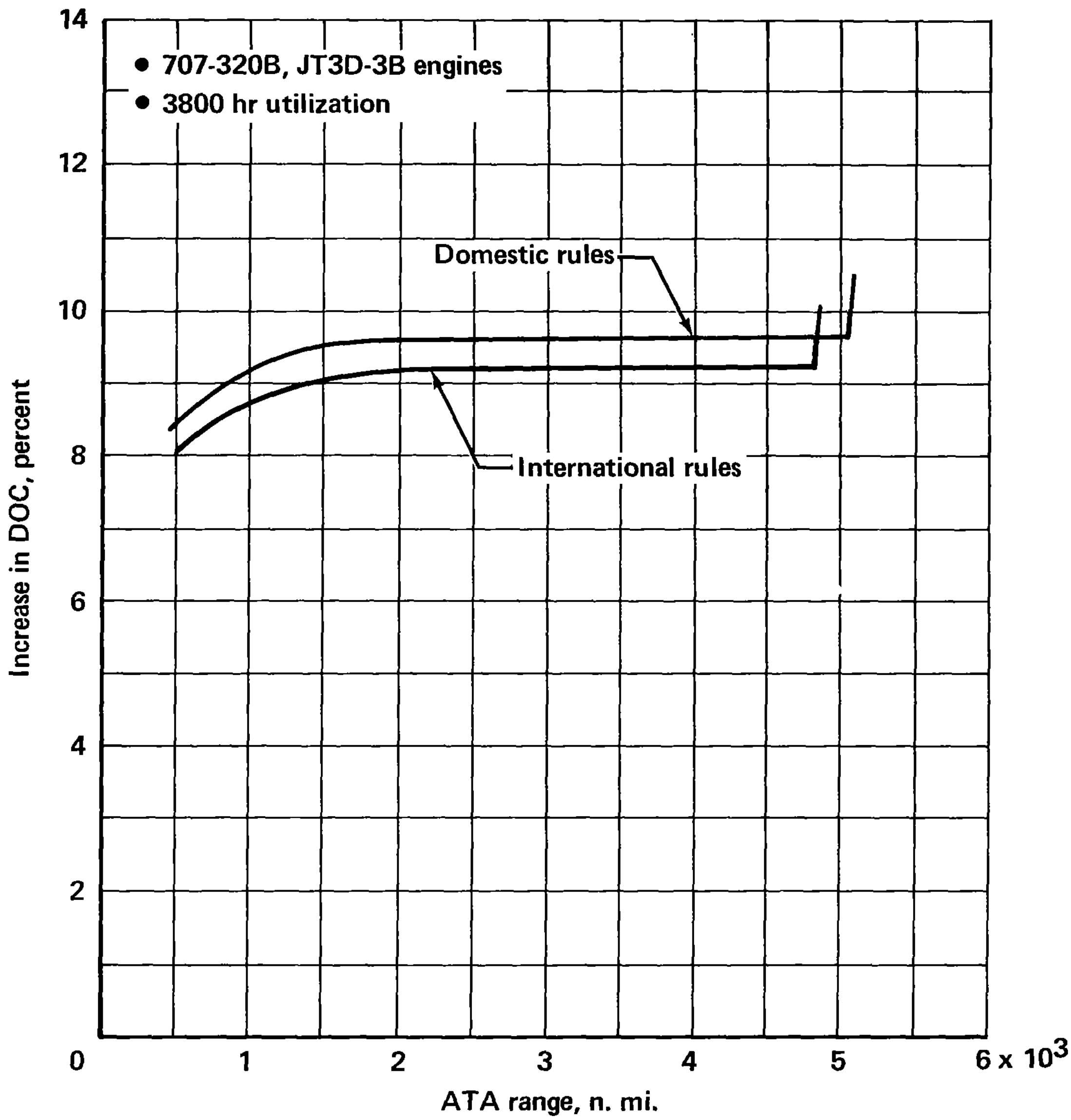


FIGURE 9.—INCREASE OF DIRECT OPERATING COSTS DUE TO NACELLE TREATMENT

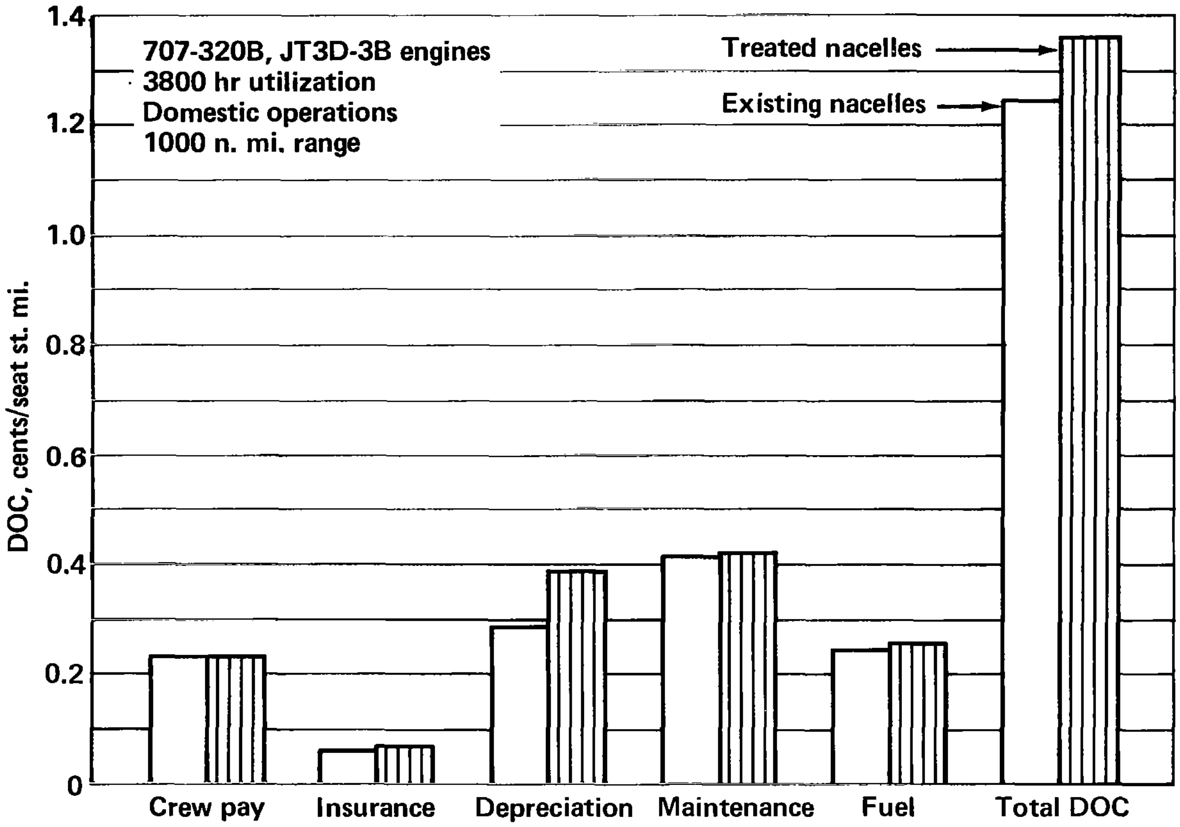


FIGURE 10.—INCREASE OF ELEMENTS OF DIRECT OPERATING COSTS DUE TO NACELLE TREATMENT

Weight	Existing nacelle	Treated nacelle
Max. gross takeoff weight, lb	327 000	327 000
Operating empty weight, lb	145 100	148 240
Max. zero fuel weight, lb	190 000	193 140

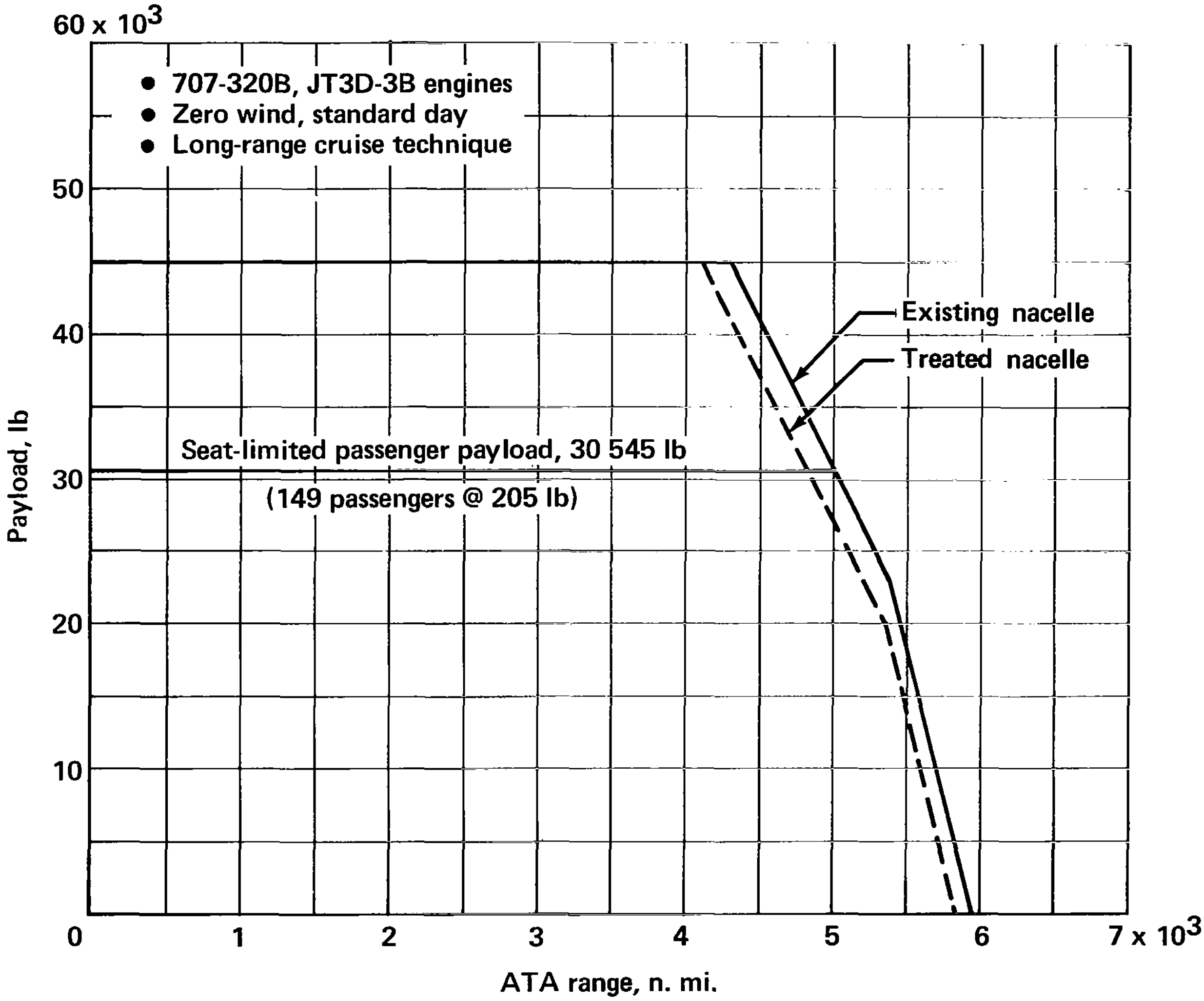


FIGURE 11.—ATA INTERNATIONAL RANGE PERFORMANCE

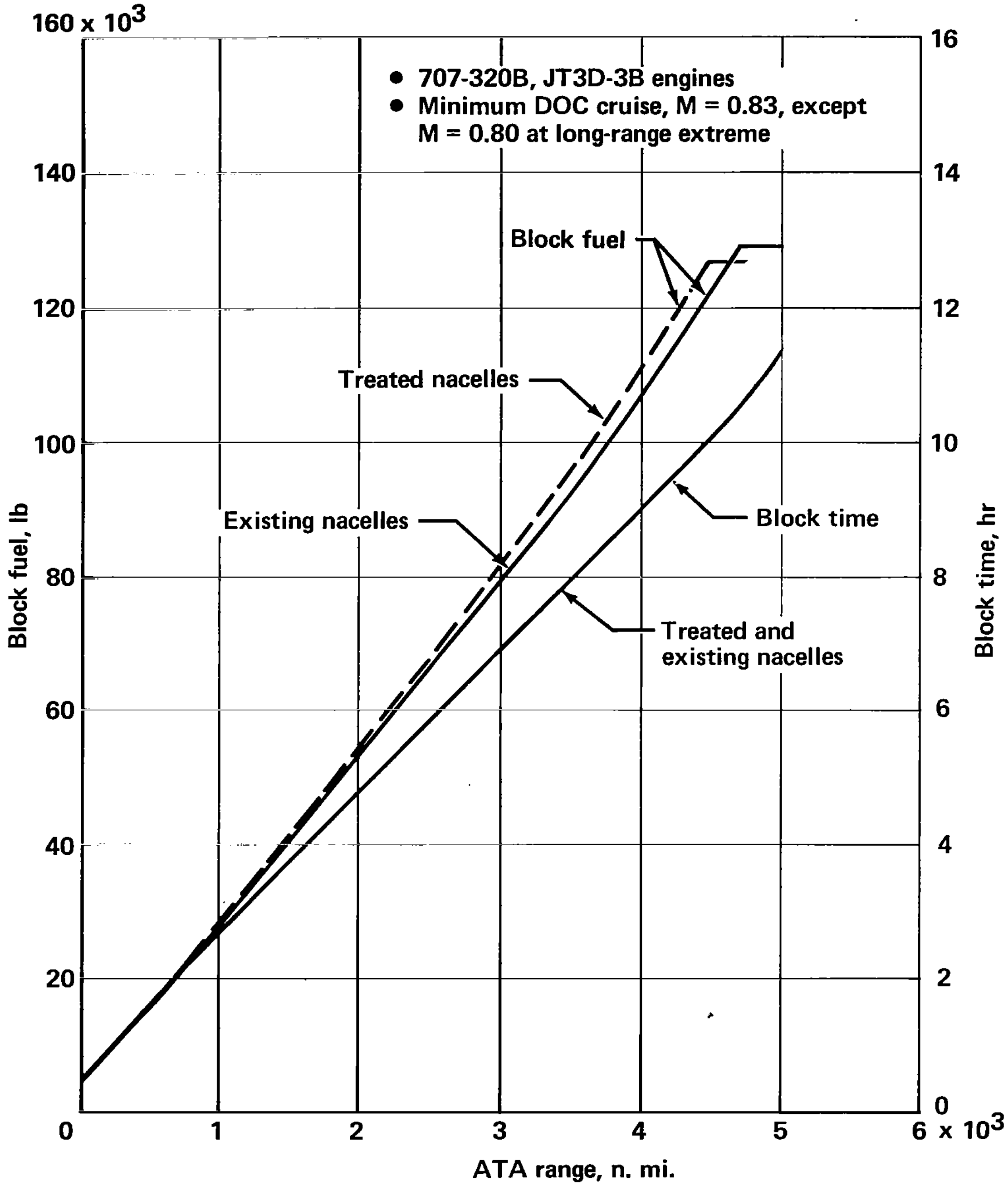


FIGURE 12.—ATA INTERNATIONAL BLOCK TIME AND FUEL

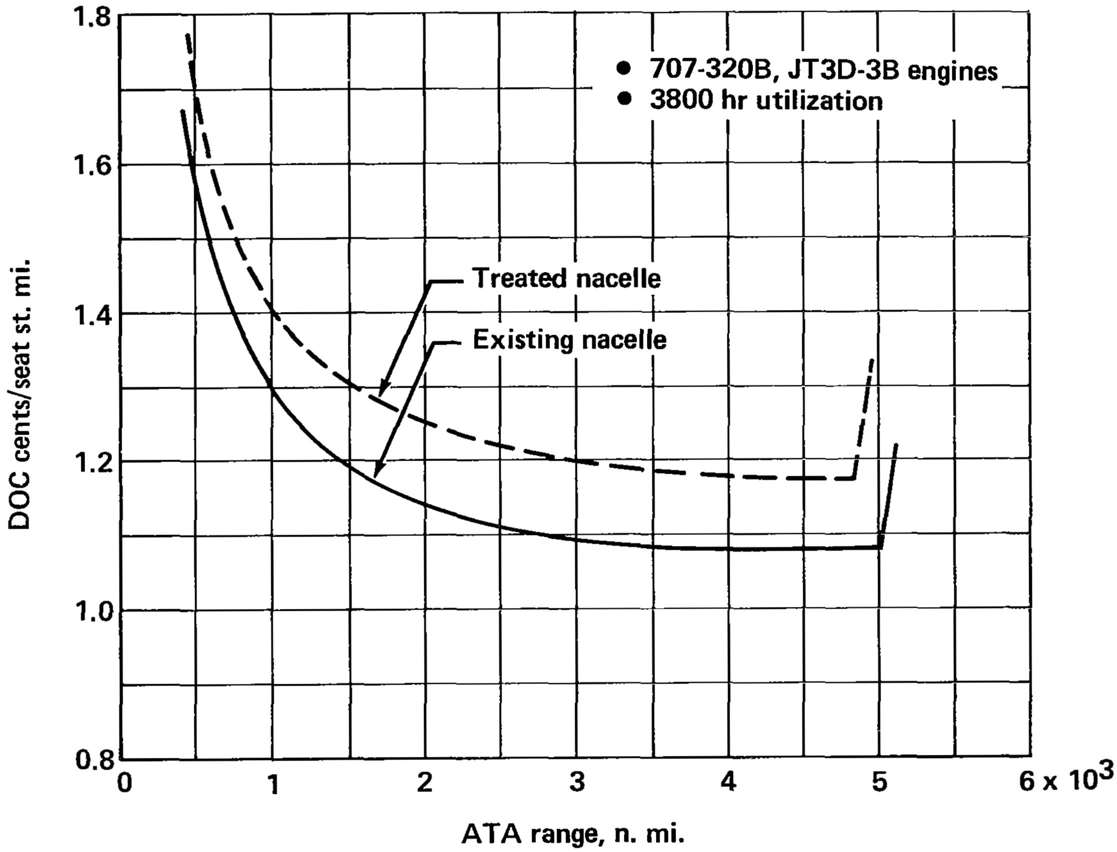


FIGURE 13.—ATA INTERNATIONAL DIRECT OPERATING COSTS

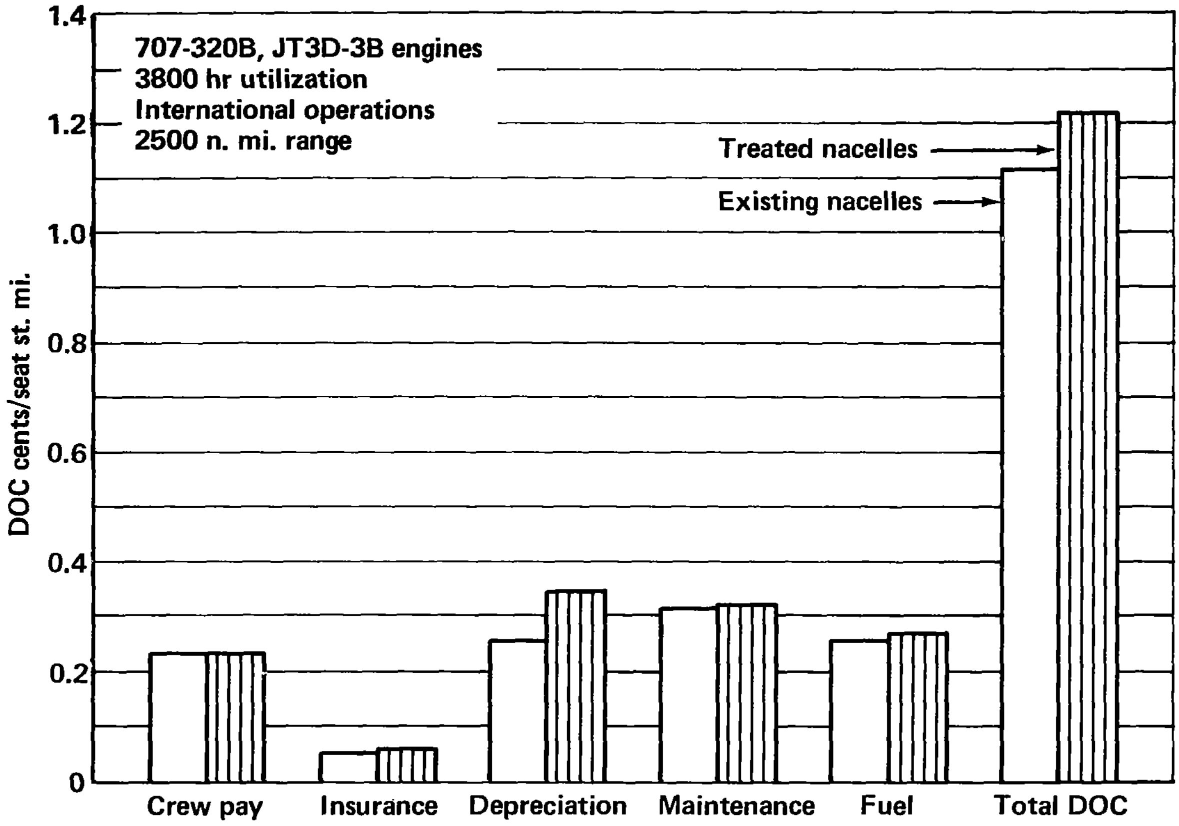


FIGURE 14.—INCREASE OF ELEMENTS OF DIRECT OPERATING COSTS DUE TO NACELLE TREATMENT

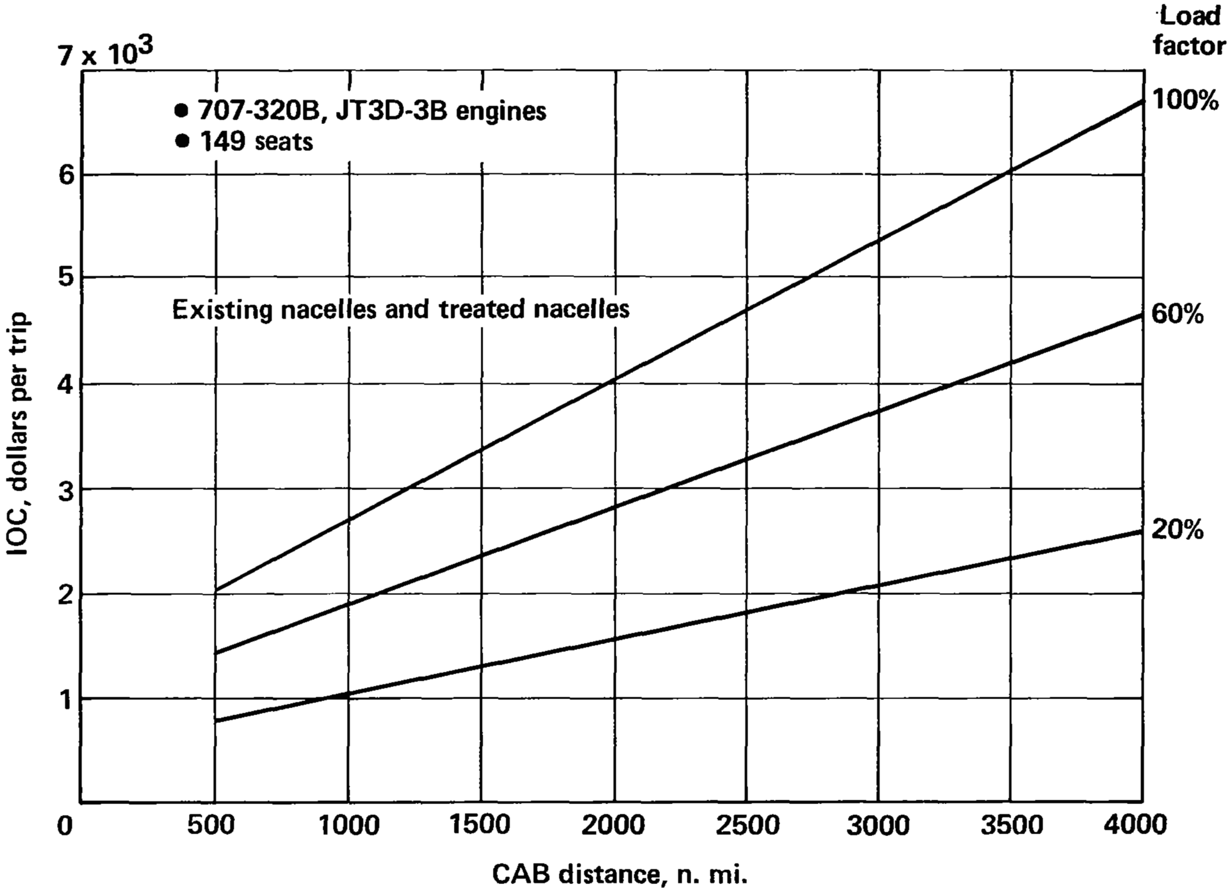


FIGURE 15.—DOMESTIC INDIRECT OPERATING COSTS

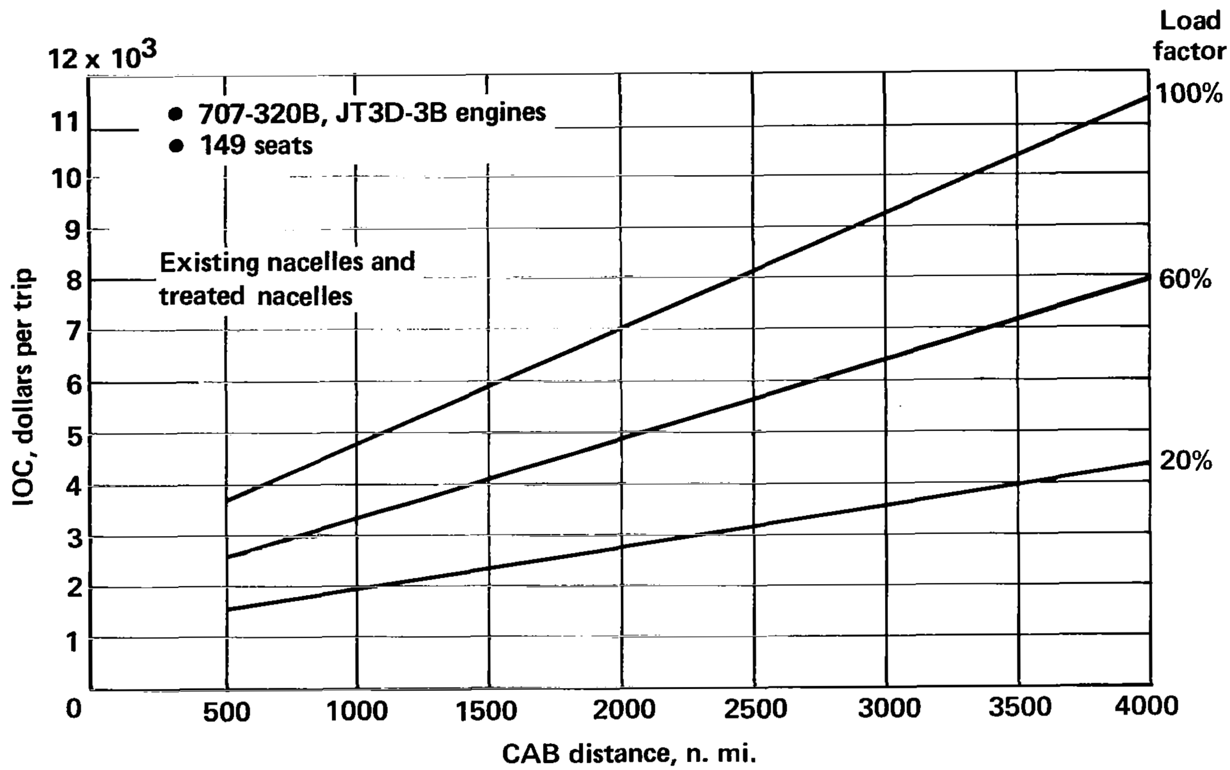


FIGURE 16.—INTERNATIONAL INDIRECT OPERATING COSTS

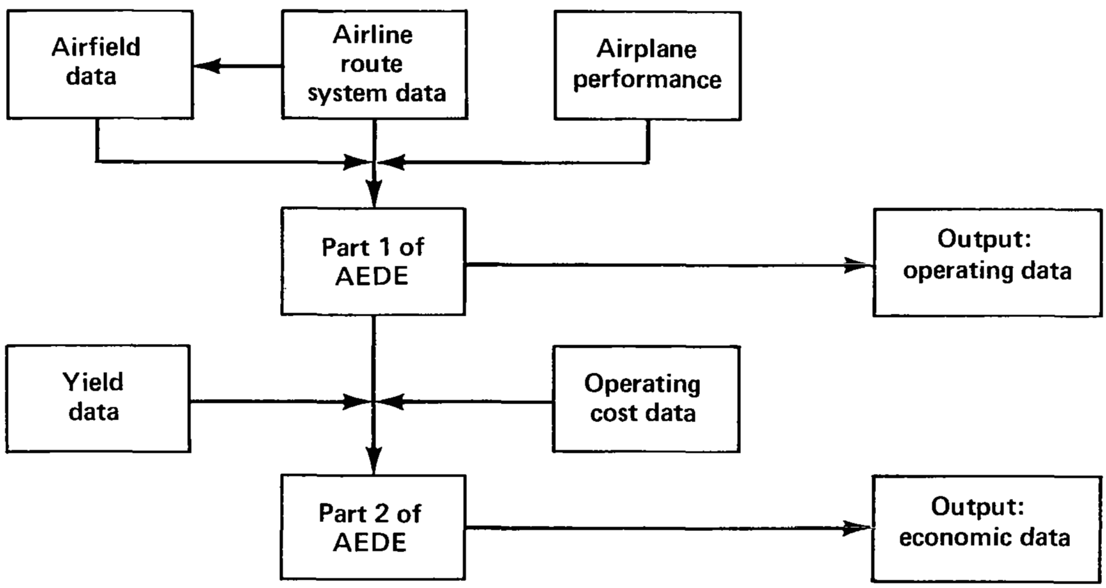


FIGURE 17.—AEDE PROGRAM DATA FLOW

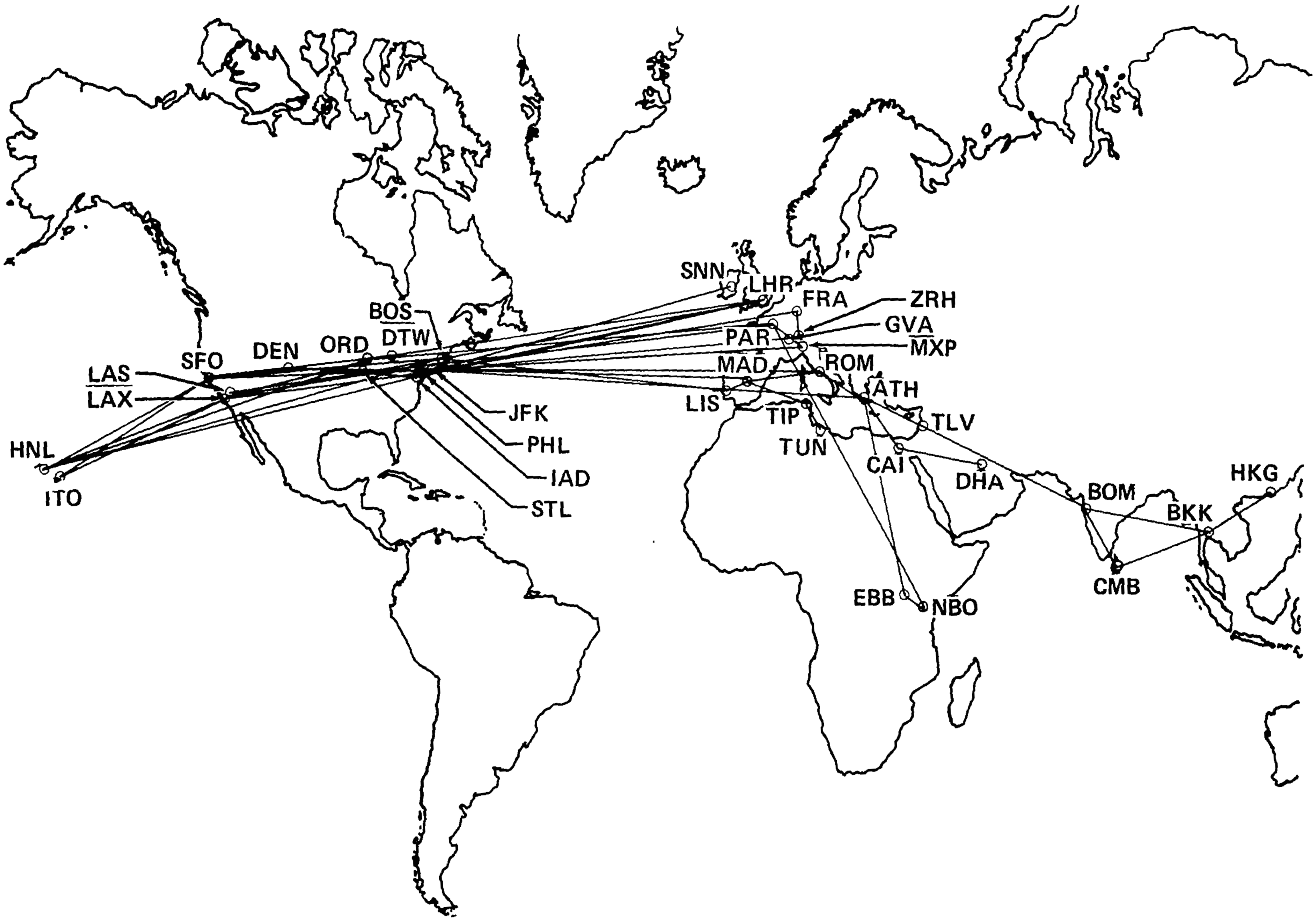


FIGURE 18.—AIRLINE ROUTE SYSTEM

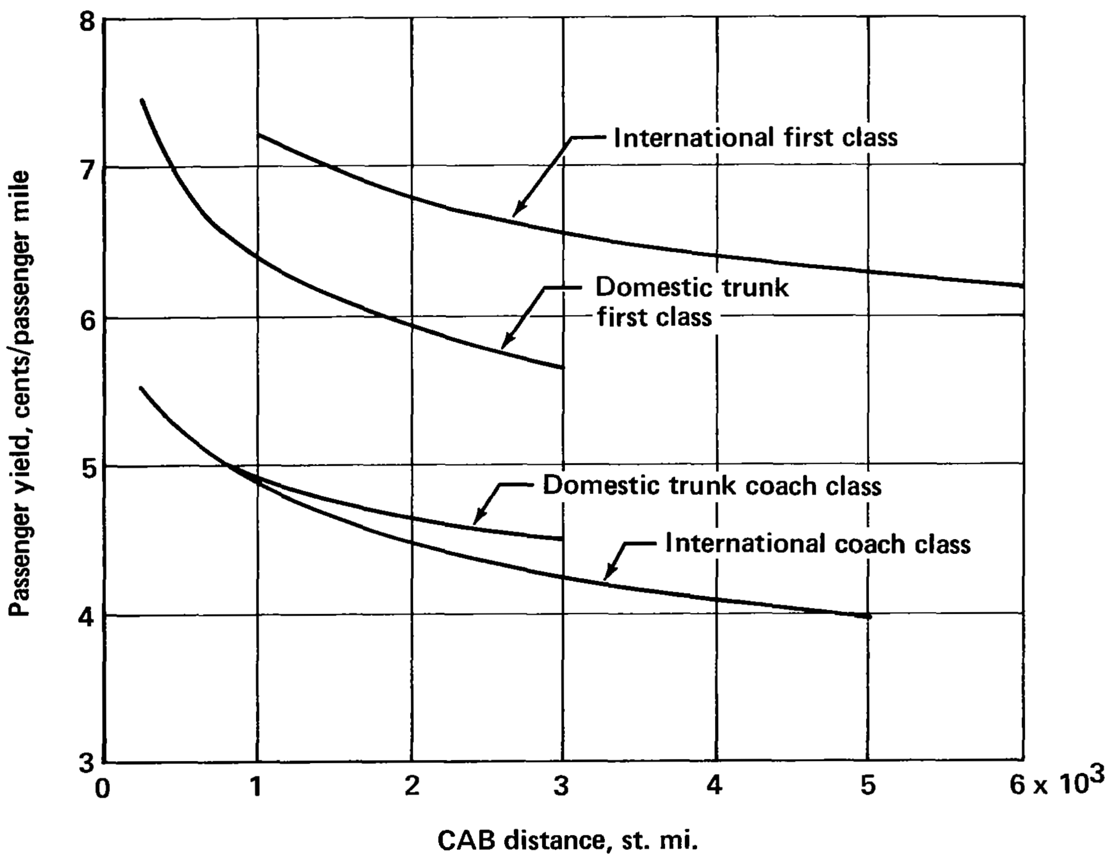


FIGURE 19.—PASSENGER YIELD

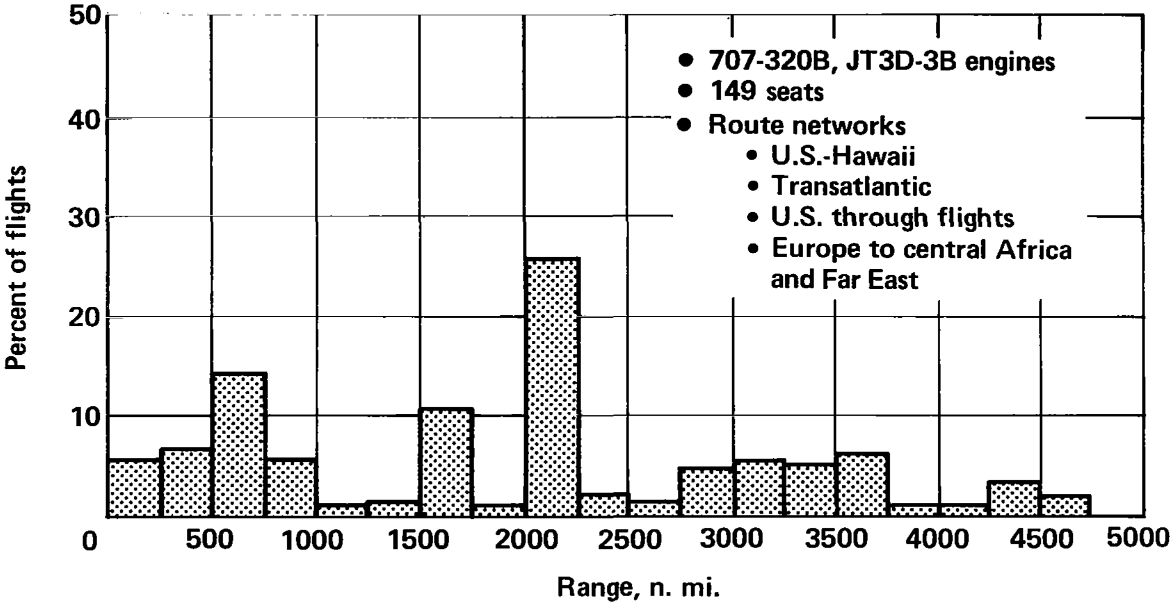


FIGURE 20.—DISTRIBUTION OF FLIGHT FREQUENCIES BY STAGE LENGTH

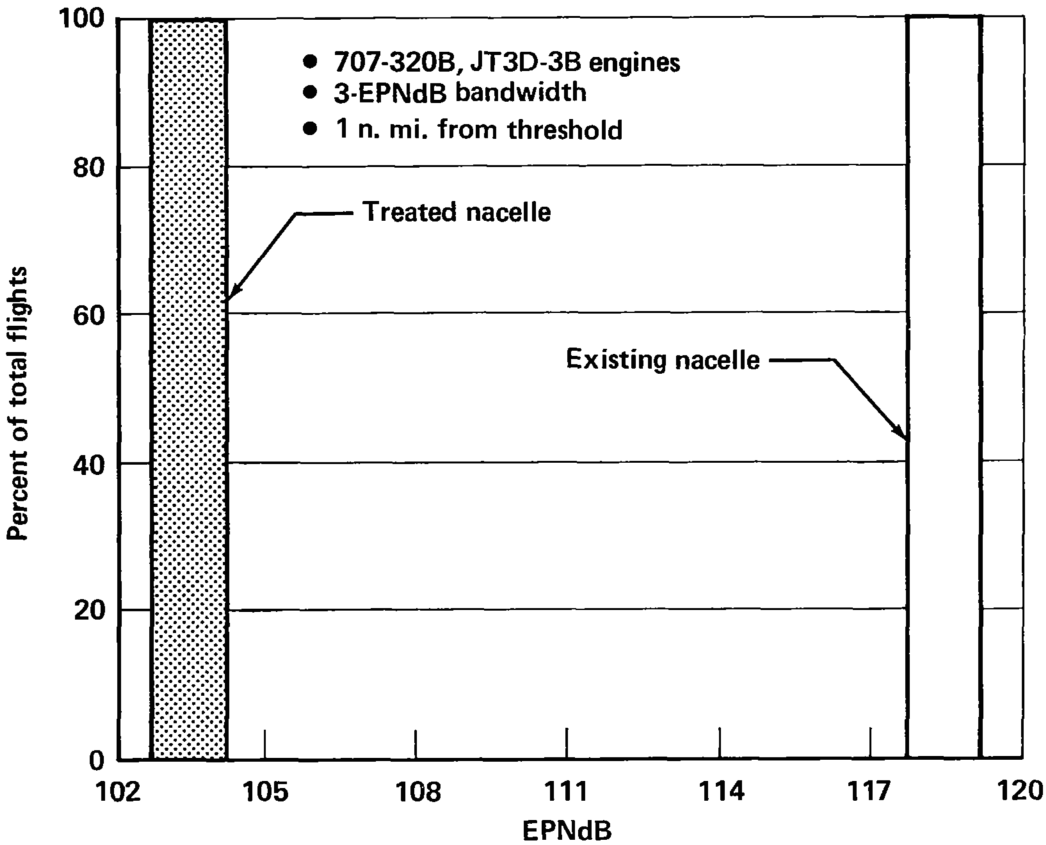


FIGURE 21.—APPROACH NOISE LEVEL DISTRIBUTION

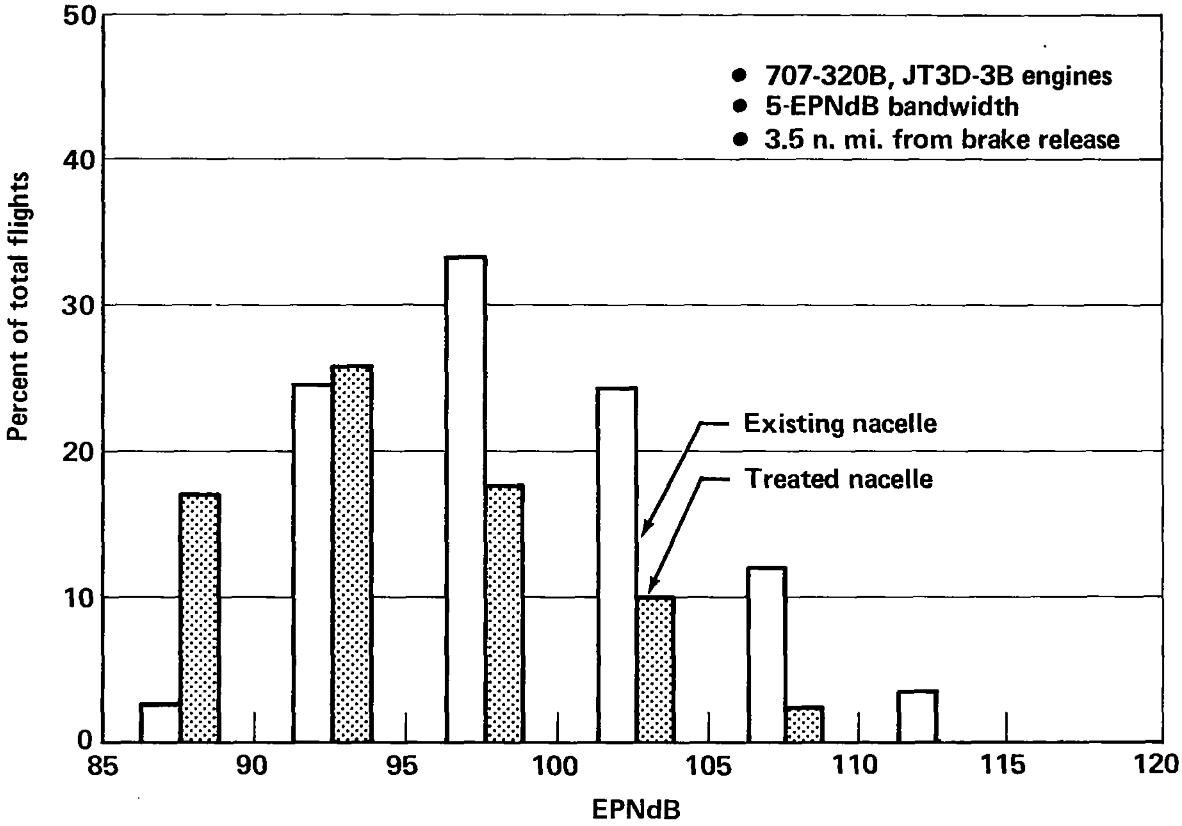


FIGURE 22.—TAKEOFF NOISE LEVEL DISTRIBUTION